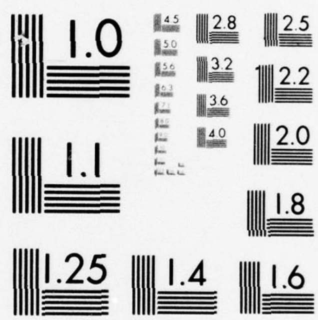
AD-A053 854 ARMY ELECTRONICS RESEARCH AND DEVELOPMENT COMMAND WS--ETC F/G 4/2
AN INTERPRETATIVE REVIEW OF EXISTING CAPABILITIES FOR MEASURING--ETC(U)
JAN 78 H H MONAHAN, R M CIONCO

UNCLASSIFIED ERADCOM/ASL-TR-0001 NL

| OF |

AD
A053854

END
DATE
FILMED
6 -78
DDC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

ASL-TR-0001

AN INTERPRETATIVE REVIEW OF EXISTING CAPABILITIES FOR MEASURING AND FORECASTING SELECTED WEATHER VARIABLES (EMPHASIZING REMOTE MEANS)

JANUARY 1978

By

H.H. Monahan
R.M. Cionco

Approved for public release; distribution unlimited.

US Army Electronics Research
and Development Command
Atmospheric Sciences Laboratory
White Sands Missile Range, N.M. 88002

NOTICES

Disclaimers

Disposition

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
ASL-TR-0001

14 ERADCOM/ASL-TR-0001

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
6 AN INTERPRETATIVE REVIEW OF EXISTING CAPABILITIES FOR MEASURING AND FORECASTING SELECTED WEATHER VARIABLES (EMPHASIZING REMOTE MEANS).

5. TYPE OF REPORT & PERIOD COVERED
R&D Technical Report

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
10 H. H. Monahan
R. M. Cionco

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Atmospheric Sciences Laboratory
White Sands Missile Range, New Mexico 88002

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
DA Task No. 16 1L161102B53A 17 SA1

11. CONTROLLING OFFICE NAME AND ADDRESS
US Army Electronics Research and Development Command
Adelphi, MD 20783

12. REPORT DATE
11 Jan[redacted]78

13. NUMBER OF PAGES
53

12 51p.

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
9 Research and development technical rept.

15. SECURITY CLASS. (of this report)
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Meteorological parameters
Remote sensing
Measurement
Predictions

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
The variability in weather many times influences significantly the decisions made in military tactical planning and operations affecting the utilization of Army weapons systems, smoke deployment for both offensive and defensive purposes, and air and ground operations.

An interpretative review has been made of many documented capabilities for measuring and forecasting selected weather variables, i.e., precipitation,

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

410 663

20. ABSTRACT (cont)

cloud cover and height, and profiles of temperature, humidity, and wind speed, that exist worldwide.

Methodologies and techniques that rely on the collection of meteorological data by remote means and numerical prediction models that are operational have been emphasized.

Available evaluation information is presented for some of the methodologies and techniques included in the report.

CONTENTS

PREFACE

The authors wish to acknowledge the support of the Mobility and Environmental Systems Laboratory, US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, in funding this work effort as part of a planned multiyear program entitled "Hydrology Support for Military Operations."

INTRODUCTION

Precipitation, clouds, temperature, humidity, and wind affect military tactics significantly in many areas, e.g., performance of electro-optical weapons systems, transport and diffusion of obscuration materials, toxic and incapacitating chemical agents and pollutants in the atmosphere, and maneuverability of aircraft.

These weather variables also present hydrologic implications to military operations, i.e., vehicular trafficability, to the extent, or degree, that each variable influences soil moisture, water supply, and streamflow. At least 90% of the variation in water runoff from a given region is caused by variations in the intensity, duration, and location of rainstorms. Snow accumulation is a problem because it is so difficult to quantify; but even if snow accumulation is known, the rate of melting assumes major importance with solar insolation becoming a significant factor probably even more than temperature. Humidity is really significant only when it is near the low end of its range where dehydration is rapid enough to be troublesome. Wind velocity coupled with low humidity effectively increases the rate of evapotranspiration.

The purpose of this report is to present an interpretative review of numerous capabilities for measuring and forecasting precipitation, cloud cover and height, and profiles of temperature, humidity, and windspeed that exist worldwide. Emphasis has been placed upon methodologies and techniques that rely on the collection of meteorological data by remote means and upon numerical predictive models that are operational.

There has been no intent to present an all-inclusive treatment of the subject matter. Many worthwhile measurement methods and forecasting techniques, including some very recent developments, have not been cited due to the limited scope of this study. It is hoped, however, that many omitted methodologies and techniques will be recognized indirectly through association with generalized statements or similarity to more detailed explanations in the report.

MEASUREMENT CAPABILITIES

Remote Sensing Methods

Remote sensing methods, i.e., those involving the collection of data by systems not in direct contact with the phenomena under investigation, have been in use for a number of years in the form of weather radar (for detecting precipitation or clouds) and other techniques [1]. Only recently, though, have concerted efforts to make full use of electromagnetic spectrum and acoustic probing of the atmosphere led to developments in Doppler radar, frequency-modulated, continuous wave (FM-CW) radar laser systems, and acoustic echo sounders that are helpful in obtaining data on all the important parameters of the lower atmosphere [2].

Remote sensing of the earth's atmosphere is often hampered by the presence of clouds of varying density over the region being surveyed [3]. However, by the end of this decade, it is anticipated that satellite sounding systems will be able to penetrate practically all cloud conditions, exclusive of precipitating clouds.

Meteorological Satellites

Since the first TIROS satellite was launched in 1960, weather predictions have been based partially on information available from orbiting weather satellites. Originally, artificial satellites were used simply for pictorial representations of cloud distribution, but now their use has extended, via the remote measurement of temperatures of land, sea, and cloud surfaces, to the reconstruction of complete vertical distributions of temperature and humidity [4].

In addition to the traditional passive sensors operating in the infrared (IR) and visible regions of the electromagnetic spectrum, a phase of satellite sensors has now begun in which microwave and radar systems are being practically exploited [5]. Radiometer scanners have provided observations (with increased improvement from medium to very high resolution) of cloud cover and severe storms, as well as observations from which tropospheric temperature and water vapor profiles can be inferred [6].

US Department of Defense Meteorological Satellite Program. The US Department of Defense Meteorological Satellite Program (DMSP) is a unique and valuable meteorological data system [7]. The sensors, communications, and data processing equipment contribute to form the most responsive operational system of its kind. Data are obtained from space-borne sensors in the visual and IR spectra. Imagery data characteristics include both visual and IR sensor resolution capability of 0.33 nautical mile (nmi) for limited areas and 2.0 nmi for global coverage. The spectral bandwidth of the visual sensors was selected to optimize the distinction between clouds, ground, and water. Electronic circuitry in the sensors converts the sensed IR energy directly to equivalent blackbody temperatures, making temperature the directly displayed parameter. The sensitivity of the 2 nmi visual channel covers seven orders of magnitude, which provides useful meteorological information from full daylight over highly reflective scenes to an illumination level roughly equivalent to half moonlight. One additional sensor furnishing data to DMSP is an eight-channel radiometer for the determination of vertical temperature and height profiles. Raw data are converted into cloud parameters and collated with conventional meteorological data to produce a comprehensive numerical cloud analysis. With temperature as the displayed parameter, the resulting enhancement of IR data allows the pinpointing of storm location as well as detailed information on storm cloud structure.

Currently, DMSP provides data sensed near dawn and near local noon and their nighttime complements. The DMSP communications and ground pro-

cessing system are designed to produce a usable product within 5 minutes of termination of the data stream. For direct readouts, a data age of 5 to 20 minutes when ready for application to operational decisions is then feasible. Data collected by the satellite are both broadcast to military receiving terminals in the satellite local area and stored for later broadcast to the Air Force Global Weather Central (AFGWC) [8]. The AFGWC is linked to its readout facilities by real-time, wide-band communications.

Soviet Union Meteorological Space System. The Soviet Union has operated a meteorological space system, "Meteor," since the late 1960's [9]. The system is based on two or, more often, three satellites of similar type launched into almost circular polar orbits at 900 km altitude. "Meteor" satellites carry scanning imaging instruments to obtain cloud images and snow and ice cover as shown by temperature contrasts on the sunlit and dark sides of the earth, as well as to measure the radiation temperature of clouds and earth surfaces.

The Soviet Union plans to develop a geostationary satellite system over the Indian Ocean, which could probably be launched by 1978. This satellite is expected to obtain images in the visible and IR ranges, collect information from instrumented ground platforms, and relay data between processing centers.

Weather Radar

As a primary information instrument, weather radar shows the shape and dimensions of weather disturbances on a screen. Weather radar can also provide information on the external shape and physical state of pluvial concentrations, as well as particle volume and density [10]. Several precipitation types (rain, sleet, snow) have been distinguished through variations in screen brightness. The hydrometeor detection capabilities of a radar set are critically dependent upon its wavelength. In general, the wavelength required to detect the particles decreases with decreased size of the particles [11].

Weather Radar Problems. Weather radar application can be quantitative, as well as qualitative, in the measurement of precipitation; however, quantitative applications require correlation between precipitation and instrument response. In the past, a widespread application of weather radar to hydrologic studies has not been realized because the large inherent variance of the radar return signal from rain has resulted in uncertain quantitative measurements of rain intensity [12].

The radar presents precipitation intensity distribution in a distorted form because of attenuation (reduction in intensity) of the electromagnetic (EM) waves in precipitation and also because of finite dimensions of the sound pulse [13]. Cloud and rain attenuation has to be considered at wavelengths below the 10-cm band and can have serious effects in the 3-cm and 1-cm bands.

Another serious obstacle to radar estimation of rain is the false echo effect resulting from anomalous propagation caused by density variations in the atmosphere [14].

In 1970, important initial efforts were made in the Soviet Union to improve precipitation and cloud measurements by means of either two sets of radar using different wavelengths or a single set of radar using two wavelengths to determine the relative absorption sustained by the two wavelengths [15]. Numerous investigations have been made by different nations during the past few years relating to precipitation intensity attenuation and depolarization (due to nonsphericity of falling raindrops) at microwave and millimeter wavelengths.

Much effort has been expended to find parameters of the radar echo distribution that are usable in specifying the best estimate of the radar reflectivity-precipitation rate (Z-R) relationship for each storm [16]. There have been numerous studies of snow/EM signal interaction, but they predominantly address falling snow with only a few addressing snow-covered radar targets or surfaces.

Any examination of the capabilities and limitations of weather radar for quantitative echo intensity measurements must consider the tradeoff among beamwidth, echo integration procedures, and scanning time limitations [17]. Fortunately, new alternatives to this problem have been presented by recent developments in electric scanning antennas, frequency-agility noise-pulse radars, and pulse compression.

<u>US National Weather Service Weather Radar Program</u>. In 1976, the US National Weather Service (NWS) began converting their weather radars to provide an automated digital data stream. Under this NWS program, digital video integrators, on-line minicomputers, and necessary automatic communications equipment will be added to existing WSR-57 radars. Federal Aviation Administration Air Route Traffic Control radars are also being equipped with weather and fixed map units which provide some weather data in digital form.

The digital video technique offers advantages for the digital processing of rainfall data for flood and trafficability forecasting. It is also suited for producing digitally integrated echo intensity contours of severe storms, and can be conveniently transmitted over land lines for remote display.

<u>Airborne Weather Radars</u>. Airborne weather radars are restricted in size of antennas carried and tend to use shorter wavelengths that attenuate appreciably in widespread or heavy precipitation [18]. Unlike land-based equipment though, these radars are continually moving at a high rate, resulting in opportunities to view a given piece of the precipitation pattern from many aspects.

British scientists have investigated the capability of airborne side looking radar (SLR) and noted the following system deficiencies:

(1) rain and snow cause system attenuation; (2) SLR resolution is not good; (3) imagery is small scale, and distortion and shadowing occur in mountainous areas [19].

Measurement of Precipitation

Quantitative measurements of precipitation apparently necessitate the use of radar having a narrow transmission beam in all planes and a wavelength which is subject to negligible attenuation. A wavelength of 10-cm seems to be the most likely to reasonably satisfy all of these conditions, although relatively large antennas and relatively high peak transmitted power are then required. At wavelengths less than 10-cm, no precise measurement can be made without a correction being made to the power returned to the radar. As a compromise, C-band (5.5-cm wavelength) radars offer the advantage of nominal precipitation attenuation combined with good detection capability for frozen and low rates of precipitation plus adequate beamwidth resolution of the echoes.

Methods of Estimating Rainfall

a. Satellite Data

Many methods have concentrated on estimating convective rainfall. In these estimation methods, regions of convective activity must be isolated from background cloudiness and the extent and significance of nonconvective rainfall must be determined. Methods using visible satellite data have tackled the first difficulty through an enhancement technique which suppresses regions of shallow convection and inactive stratiform clouds by setting a cloud brightness threshold. Typically, radiance response on meteorological satellites is set such that the upper 10% to 40% of the brightness range contains the regions of deep convection. Similarly, IR techniques try to discern regions of convective activity and estimates of rainfall by comparing equivalent blackbody temperatures to climatological, regionally arranged, or actual temperature soundings. Both methods are flawed. Brightness enhancement suffers from signal saturation and dependence on sun angle and viewing geometry; while the IR method is compromised by cirrus contamination and resolution.

By comparing satellite brightness contoured cloud masses with contoured radar echoes, it appears possible to use satellite pictures for inferring precipitation frequency (occurrence), extent, intensity, and rate of change.

A method developed in the Soviet Union visibly identifies precipitation and gives an approximate estimation of its intensity using satellite microwave measurements on two orthogonal polarizations at the 0.8-cm region [20]. Developed from computational data of microwave radiation intensity, this method is based on the dependence of absolute values of radio brightness temperature measured on vertical and horizontal polarizations and their difference on total content of water vapor and liquid

water in the atmosphere. This method makes it possible to identify cloud formations and zones of precipitation, and to approximate the integral water content of clouds and rainfall intensity.

b. Other Remote Techniques

Dual- and multi-Doppler radars have been used to specify the dimensional particle velocities within convective storms as related to heavy rainfall. The drop size distribution in rain (with difficulties involved in the case of snow) can be computed from the Doppler spectrum, provided the updraft velocity can be estimated [21]. Definite seismic and acoustic intrusion sensor activation patterns have also been correlated with various rainfall rates [22].

Monostatic lidar has been explored as a means of determining the rainfall rate over an extended atmospheric path [23]. In accounting for the multiple scattering of light in rain, estimates have been derived for the optical extinction coefficient of rain as a function of range from the lidar returns. Lidar soundings of the atmosphere under a variety of conditions (snowfall, rain, drizzle, etc.) have given sharp polarization differences of signals that can be used to identify the meteorological characteristics of hydrometeors [24].

The Environmental Research Laboratory, NOAA, has been probing various weather systems by use of multiwavelength lidar combined with shortwave radar and IR radiometry [25]. Of particular interest is a laser probing system that uses a flashlamp pumped dye laser as the radiation source and a plastic (Fresnel) lens in the receiver to collect the radiation backscattered by the atmosphere [26]. This system is claimed to be less expensive, more reliable, and more compact than systems incorporating ruby lasers and more conventional receiver optics.

c. Rain Gages

The tipping bucket precipitation gage, weighing-type rain gage, and the Jardi rate-of-rainfall gage are just a few of the many precipitation measuring gages used throughout the world. However, during recent years, new improved instrumentation has been developed to increase the accuracy of precipitation measurements. The Workman intensity gage which senses the flow of water down a movable trough and the Raymond-Wilson gage which measures the electrical resistance of flowing water are both superior to standard gages because of their rapid response time and capacity to measure high intensity showers continuously and automatically [27]. A recording rain gage, with electronic sensors and circuitry to provide a sensitivity of 0.1 mm in recording, permits the accurate sensing of mists and drizzle, as well as rainfall of almost any known rate [28]. A laser rain gage measures precipitation by the scattering of light from raindrops. The sampling medium is a collimated beam from a helium-neon laser. The amount of light scattered is a function of the number and size of drops intercepting the beam; an equation relating rainfall rate and scattered light is derived.

Some scientists have visualized that radar (which can observe precipitation over a very large area) ultimately will replace rain gages. Others have taken the position that radars should complement rain gages and that, when used together, they will provide significantly better information on rainfall than can be obtained from a rain gage network alone. In general, investigators have shown that radars, properly calibrated with a rain gage in the area, can make reasonably accurate measurements of rainfall intensity and accumulated rainfall over a small watershed.

Snow Measurements. A disdrometer technique for measuring snowflake size distributions uses a pulsed ruby laser which stops particle motion and provides instantaneous periodic samplings over the history of the particles [29]. An acoustic device that tallies all particles over 20μm provides an accurate count of large snowflakes falling into the sensor [30].

A new type of dilatometer has been designed to determine the free water content of wet snow within an error of 1% from the decrease in volume caused by the process of melting snow [31].

The use of natural gamma radiation from the soil as a basis for snow-water equivalent measurements at remote sites has been under investigation by the NWS since 1970 [32]. Results have indicated measurements with about 5% error in the 5-40 cm water equivalent range during periods uncomplicated by precipitation or considerable change in soil moisture. It has also been found that airborne measurement of the areal average of the water equivalent of snow by the terrestrial gamma attenuation method is accurate to 1.2-cm, or 10%, whichever is greater [33]. This method has good potential for large, rapid, areal measurements of water equivalent over flat or rolling terrain. The attenuation of highly penetrating cosmic radiation appears to have excellent potential for measuring the water equivalent of snow cover in extremely deep snow. A two-scintillation detector setup, one above and one beneath the snow, has produced a water equivalent measurement accuracy of better than 1% in measuring 100 cm of water with a 24-hour measurement time [34].

Remote sensing of snow cover by SLR, with wavelengths of 1 cm or smaller, has provided quick, comprehensive information about snow depth, density, and water content [35].

Visible and near-visible light sensors carried on meteorological satellites can also measure the snow area extent, but cannot routinely detect snow under clouds or a forest canopy. Furthermore, much research needs to be done on the electrical (including scattering) properties of snow before efficient all-weather remote sensing systems can be designed [36].

Hail Sensing Instruments. Surface in situ hail sensing instruments have been classified into two major categories [37]. The integrating sensors include the hailpad, hailstool, hail cube, and hail-wind detector. Time-recording sensors include the Geophone hailgage, Illinois Water Survey hailgage, NOAA hail momentum sensor, and a hail-rain separator.

The integrating sensors are relatively inexpensive and yield useful data, including estimates of wind effects. The recording type is 10-100 times more expensive, but for this additional cost, obtains detailed time information that is not available from integrating instruments.

A recent developmental effort in remote hail detection has been the dual-wavelength radar hail detection technique proposed by Eccles and Atlas [37]. Based on the variable scattering properties of hail at different wavelengths, this approach has met with limited success. Another radar hail detection technique is based on the depolarization of microwave radiation by nonspherical hailstones. Tests of this approach in Canada have lent support to its validity.

A theoretical investigation has shown that the ratio of radar reflectivity factors at 10 cm and 3 cm wavelengths is useful in delineating hail regions and can also be used to estimate mean hail diameter under certain conditions [38]. Regions of hail can be identified as regions of large ratios after taking attenuation into account where necessary.

Measurement of Cloud Amount and Height

Weather Satellite Applications. The application of weather satellites has been a milestone in the monitoring of large-scale cloudiness, even though the utility of meteorological satellite data is currently limited because of an inability to precisely define the heights and small-scale structure of clouds. Satellite cloud photographs have been used to determine the approximate altitude of clouds by applying an approximate equation that relates cloud altitude, angle of sun elevation, and cloud image to corresponding shadow distance as measured directly on the photograph [39]. Another rapid objective method calculates the horizontal dimensions of cloud systems based upon the height of satellite orbit, dimensions of the picture taken, and view angle of the TV camera [40].

Satellite digital images have also been used to study the time-changing cloud and thermodynamic structure of cloud clusters and their environment over the oceans [41].

Characteristic features and temporal variations of clouds have been obtained from cloud brightness data and radar plan-position indicator (PPI) pictures. From the PPI display, one can immediately read the range and bearing to the target. A comparison of radar heights of large cumulus clouds to their reflected solar radiance has shown strong correlation (0.88), thus suggesting that cumulus cloud heights and growth may be inferred from a satellite platform without use of ground-based radar [42].

Other Methods for Evaluating Cloud Amount. An automatic cloud-amount recorder developed by the Swedish Meteorological and Hydrological Institute is based on the principle that each cloud element is characterized by a certain temperature at the cloud base and a certain aperture angle from the place of observation [43]. By measuring the tempera-

ture and knowing the temperature profile from the latest radiosonde measurements, it is possible to decide whether the cloud is a high, middle, or low cloud and to determine the cloud size. The model recorder, equipped with rotating aluminum mirrors and IR thermometer, scans from 90 to 40 degress above the horizon. Three different temperature layers (corresponding to high, middle, and low cloud) are selected at three potentiometers, giving three reference voltages. The signal from the IR sensor is fed to a level detector with three outputs, which indicate that the cloud is detected at the corresponding cloud level. Out of such signals, the amounts (in eights of sky coverage) of high, middle, and low cloud are integrated. Reasonably good results were obtained as compared with manual observations.

Other instruments have also been built to evaluate cloud amount [44]. One is based on the difference in the IR emission of clouds and clear sky and uses, as a sensor, a net radiometer with screening consisting of a thin metal sheet blackened on the internal face. Another exploits the intensity of sky light in the two extreme visible regions. Two filters and two sensors are used to evaluate the fraction of polarized light in sky light. A sky mirror system has been used to take pictures of the whole sky, with the clouds being projected perpendicularly upon the plane of the horizon to form a cloud cover map [45]. All-sky camera photographs have been used to determine low, middle, high, and total cloud cover, in addition to diurnal cloud variations over ocean areas.

Measurement of Cloud Height. Various devices have been used for determining cloud height [46]. Many stations use automatic ground-based ceilometers, e.g., fixed beam ceilometer, rotating beam ceilometer and an eyesafe laser ceilometer, to make cloud height measurements; with manual techniques, e.g., human estimation, ceiling light, and ceiling balloons being used as secondary systems [47]. Cloud height measuring equipment at the Berlin (Germany) Meteorological Institute includes an X-band vertical radar (former PPI radar), a stereotelemeter, and a ceilograph (ceiling projector with pulsed light) [48].

In 1972, the Japanese announced the testing of a prototype laser radar system which transmits a pulsed laser light and emits a much shorter wavelength than that of the conventional microwave system [49]. It was claimed that this system is capable of producing scope images of both thick and thin clouds, cloud thickness, fog, rain and snow. As related to laser investigation of clouds, the influence of molecular and aerosol scattering and of molecular absorption upon the magnitude of reflected echo signals has been evaluated [50].

The US Air Force Geophysics Laboratory has evaluated a ruby lidar ceilometer for applicability to cloud heights [51]. It was concluded that lidar indicates an accurate presentation of cloud structure and is superior to a standard rotating beam ceilometer as a cloud height measuring device. The US Army has been developing a portable cloud ceiling and visibility sensor through application of the AN/GVS-5 Laser Range Finder. Cloud heights are measured by reference to the time lapse from transmitted to detected signal [52].

Airborne IR scanners have also been used to obtain stereo imagery of clouds from which cloud forms and stratification, including cloud base and top heights, have been determined.

Measurement of Temperature, Humidity, and Windspeed Profiles

Temperature Profiles

a. Radiance Measurements

IR radiance measurements to obtain absorption and emission data for temperature and humidity profiles have been made by sensors based on the ground and water (buoys) as well as sensors carried aloft by aircraft, balloons, high-altitude rockets and satellites [53]. Vertical temperature profiles are derived from satellite radiation measurements by inverting the integral form of the radiative transfer equation [54]. Instrumentation for IR soundings on the basis of thermal radiation includes the Michelson interferometer, gravity spectrometers, filter radiometers, and microwave detectors [55]. In the limb scanning technique, emitted radiation from the atmosphere is measured by a radiometer as it scans across the planetary limb, with the measurements being inverted to obtain the atmospheric temperature structure [56].

The solar occultation technique, based upon measurements of the sun tangentially through the earth's atmosphere from a satellite, provides profiles of upper air temperature (by inversion) from absorption spectra data for minor atmospheric constituents [57]. Vertical resolution and sensitivity have been found to be greater for the occultation technique than for the radiance technique of measurement.

A ground-based IR spectroradiometer has been used to measure the vertical temperature profile of the lower atmosphere from the surface to 6 km. The resultant profile had an accuracy comparable to that of radiosondes [58].

Temperature profiles have also been inferred from ground-based radiometric observations of the emission by atmospheric oxygen through a quasi-linear integral equation relationship [59].

b. Laser-Lidar Methods

Measurements of atmospheric temperature profiles have used, as a physical basis for the measurements, the temperature sensitivity of the envelope of the Raman rotational band backscattered from the N_2 and O_2 content [60]. The measurements were made by a laser radar which used a dual optical channel configuration in the receiver; thus, the backscattered radiation is split between the two channels, each of which contains a narrow band optical filter designed to pass a prearranged portion of the rotational spectrum. A typical lidar differenced signal (scope trace) is presented. Future plans call for implementing the lidar with a transient recorder - minicomputer receiver package to provide not only

the sensitivity needed, but also on-line temperature profiles.

A large laser radar system has been built for use in measuring Rayleigh and Raman scattering in two colors from the atmosphere [61]. The two color capabilities of the system are used to obtain data on the differences between Rayleigh and Mie scattering which exhibit different scattering functions of different wavelengths. This laser radar has proven to be effective in obtaining data on clouds, layering of water vapor, and other inhomogeneities that are difficult to measure.

The thermodynamic distribution within a molecular absorption band of a gas has been probed by means of lidar, although relatively weak absorptions are involved [62]. Another laser method of determining the atmospheric temperature distribution is based on measurements of the combinational light scattering ratio of Stokes to anti-Stokes constituents [63].

c. Acoustic Techniques

Spectral broadening of acoustic and radio waves scattered by atmospheric turbulence has been studied, with special emphasis on Doppler radar applications [64]. A single formalism has been derived for the scattering of both acoustic and electromagnetic waves which accounts for the spectral broadening resulting from the deformation of the turbulent medium, the finite size of the observed volume, the bulk motion of air through this volume, and the pulse modulation. The backscatter spectrum associated with each of these broadening mechanisms has also been computed.

A relatively new technique for the remote measurement of temperature in the lower atmosphere employs the Radio Acoustic Sounding System (RASS) [65]. A burst of sound propagating upward in the air is tracked by Doppler radar. Air temperature at each height is determined from the instantaneous speed of the sound pulse, and a complete profile can be obtained in a few seconds. The RASS penetrates clouds, heavy pollution, precipitation, and low-level inversions. It has a temperature error much less than 1°C from near ground level to 1-3 km for most wind conditions, and is a much more cost-effective procedure than the radiosonde technique.

Backscatter echoes from acoustic tone bursts have been compared with temperature profiles measured by radiosondes through the height range of 50-700 m [66]. In tests, the sounder recorded a somewhat lower temperature inversion than radiosonde data indicated, probably because the sounder has an advantage of continuously monitoring the inversion structure and undulations produced by wind shear.

<u>Humidity Profiles</u>. The measurement of atmospheric water vapor using the Raman backscatter from a pulsed laser is feasible [67]; and the possibility of deriving humidity profiles from the backscatter of acoustic radar signals has been confirmed [68]. Humidity profiles have also been determined by lidar measurements within, and adjacent to, a water vapor absorption line [69].

But consideration of the effects of temperature and pressure on the determination of water vapor densities from ruby laser radar returns has brought forth the suggestion that water vapor densities be deduced from the line strength, which is independent of pressure, rather than from the absorption coefficient [70]. However, the accuracy of measuring water vapor concentration and atmospheric humidity by laser radiation scattering is dependent upon the errors of measuring the scattered radiation intensity and radiation wavelength [71]. The inference of water vapor profiles from ground-based remote measurements of spectral radiances has indicated that a fine-scale detailed profile structure cannot be reconstructed through the linear inversion technique which linearizes the radiative transfer function, but a nonlinear iteration technique, which minimizes the root mean square residual of the random noise along the direction of steepest descent, can be used to infer a reasonably stable solution [72].

Wind Profiles

a. Loran NAVAID System

Rawinsondes, dropsondes, and pilot balloon (pibal) observations have all been used routinely for many years to obtain vertical wind profiles. But to provide more accurate wind measurements, equipment of more recent vintage is available. The Loran NAVAID system for measuring the vertical profile of wind is capable of a 1.4-knot accuracy, and the Omega equipment an accuracy of 4.3 knots, within a 600-m height interval [73].

b. Dropwindsonde System

During the GARP Atlantic Tropical Experiment (GATE) in 1974, a unique windfinding system, called a dropwindsonde, was used in field operations for the first time [74]. Deployed from an aircraft flying at about 10 km altitude, the dropwindsonde transmitted vertical profiles of horizontal winds, pressure, temperature, and humidity, while descending on a parachute at the rate of 25 mb/min. The sonde has four sensors, including a bead thermistor for temperature, a carbonhygristor for relative humidity, and an improved aneroid cell for pressure. Windfinding is accomplished by phase measurements of Omega navigation signals received and retransmitted by the sonde to the aircraft.

c. US National Weather Service "NEXAIR" System

During the past few years, the NWS has made considerable progress in developing a new upper air sounding system (NEXAIR) that will satisfy projected requirements for large- and small-scale upper air data [75]. Using navigational aids and a nonrotating antenna system under minicomputer control, 403-MHz frangible sondes will relay pressure, temperature, and humidity data to the ground by telemeter. NEXAIR promises to be a safe, cost-effective, low-maintenance system capable of being operated in a wide variety of extreme environments.

d. Jimsphere Technique

The Jimsphere technique, which involves the tracking of a spherical balloon by a high precision radar (FPS-16) system, has provided an improved method for obtaining vertical wind profile data at 25-m intervals from near the ground to 18 km [76]. As an improvement to this system, a lightweight temperature sensor (Jimsonde) was developed to give high resolution temperature data for each 25-m height interval simultaneously with the wind data [77].

To measure wind profiles more rapidly, and to improve spatial and temporal resolution, new devices are being developed that use electromagnetic and acoustic waves to measure winds remotely.

e. Doppler Techniques

Vertical wind can be measured acoustically with a single axis monostatic system. The Doppler shift of the returned signal is related to the vertical velocity of the scattering volume, which is the vertical component of the wind. By tilting the single monostatic antenna, a component of the horizontal wind can also be measured. A weakness in making measurements with a monostatic system is that the return signals are not always continuous under some types of thermal structure. The use of a bistatic system, where transmitter and receiver are separated, helps to solve this problem.

The acoustic-Doppler technique measures the motion of wind-carried eddies from the Doppler shift of backscattered acoustic pulses. It can measure wind profiles up to 0.5 km, but is ineffective in precipitation and in high winds. Acoustic absorption also imposes height limits.

Doppler lidars measure the velocity of wind-advected aerosols and so depend on the presence of such aerosols. Furthermore, they are vulnerable to attenuation by precipitation. Another problem is that CW Doppler lidars have a range resolution that degrades as the range is increased.

The METRAC Positioning System is a self-contained, ground-based, radiolocation system that uses the Doppler principle to track a lightweight, expendable transmitter. The purpose of the system is to provide an economical, versatile, and accurate technique for tracking meteorological balloons [78]. In field tests, by tracking the same balloons simultaneously with a prototype METRAC system, the rawinsonde system, and theodolite equipment, it was concluded that the METRAC system is capable of providing high resolution wind profiles.

A Doppler radiosonde system called the Safesonde is a minimum weight, mininum cost, and minimum hazard sounding system for measuring the winds from the surface to 15 km [79]. This system consists of a simple balloon-borne transmitter tracked by five receivers to provide position data.

f. FM-CW Microwave Radar Technique

Another new technique for measuring winds in the lower atmosphere with a microwave radar is an extension of the well known FM-CW technique, and it has the same advantages of relatively low cost and high flexibility for a clear-air radar. The microwave technique, in principle, is immune to most of the factors that limit the usefulness of the optical and acoustic techniques. This technique offers an all-weather measurement capability; winds in the clear air can be measured to heights in excess of 1 km, using microwave FM-CW radar (10-cm wavelength and two identical 8-foot parabolic antennas for transmitting and receiving the signal) with Doppler processing [80]. With higher power and larger antennas, there should be a capability to probe greater heights. Aside from system parameters, the maximum radar range depends on the availability of turbulent scatterers. Nevertheless, radar wind measurement offers significant improvements in spatial and temporal coverage over in situ techniques.

Ground-Based Remote Sensing Limitations

The applicability of multi-frequency backscatter acoustic radar for monitoring vertical humidity profiles, Doppler radar for measuring temperature and wind velocity, and polarized bistatic backscatter lidar for measuring temperature and air density is currently under investigation.

However, it should be pointed out that important limitations currently exist in the ground-based remote sensing of meteorologically significant parameters [81]. For example, most optical and IR measurement systems have greatly reduced measurement capabilities in fog, cloud, or precipitation. On the other hand, some radar systems require the presence of precipitation (or chaff) to provide echoing targets. Acoustic systems are usually adversely affected by the impact noise produced by rain or hail, but (unlike optical systems) they are not adversely affected by cloud or fog.

FORECASTING CAPABILITIES

Two differing viewpoints exist concerning the laws of atmospheric movements and how to forecast them. One viewpoint is based on the assumption that the laws of atmospheric movement are relatively fixed and that with enough observational data, a set of equations on atmospheric motion could be computerized and accurate weather forecasts produced - this is numerical forecasting. The other viewpoint entails the premise that the laws of atmospheric motion are random, and that regardless of the size of the observational base, atmospheric processes cannot be completely described and probability methods must be used - this is probability forecasting.

Numerical Prediction Models

The simplest atmospheric models used in numerical weather prediction are based on the assumption of a barotropic atmosphere [82]. Individual

barotropic models differ with regard to structure, but have substantially the same characteristics in that they do not include the transformation of potential into kinetic energy.

Most numerical models, for extended range prediction, use primitive equations of hydrothermodynamics that are integrated over either the hemispheric or global domain with varying vertical resolution [83]. Depending on their purpose and current state of development, the models differ considerably in their way of treating the physical processes. Different finite-difference approximation techniques are used with various degrees of parameterization of the atmospheric boundary layer, cumulus convection, radiation and topography. Recent advances have included the development of numerical models suitable for studying the general atmospheric circulation for application to extended-range predictions.

Semi-implicit schemes (for increasing the effectiveness of computational forecasts for 5-7 days and more) have also been applied to the integration of a system of primitive equations describing a baroclinic model which recognizes atmospheric energy conversion from potential to kinetic energy [84].

US National Meteorological Center Models. Since 1966, a hemispheric six-layer baroclinic model which uses the primitive (Newtonian) equations (PE) has been used as the National Meteorological Center (NMC) operational model [85]. A regional Limited-Area Fine-Mesh (LFM) model was added in 1971. The forecasting community in the US now receives forecasts out to 48 hours from the barotropic hemispheric PE and regional LFM models twice each day, based on analyses made from 0000 and 1200 GMT observations. The PE model is also run out to 84 hours, once per day, from the 0000 GMT observations.

Use of Statistics and Climatology in Forecasting

Numerical prediction is just one weapon in the forecaster's arsenal; statistical methods, extrapolation techniques, and empirical rules will continue to have their place in weather forecasting for the foreseeable future.

In recent years, synoptic-statistical and hydrodynamical methods, along with statistical climatology, have been applied to both short-range and long-range forecasting. Modern developments in statistical meteorology have included the areas of stochastic-dynamic prediction, statistical weather forecasting, probability forecasting and time series analysis [86]. Short-range forecasting approaches have been based on statistics, local climatology, a combination of climatology and persistence, and the use of multiple prediction statistics, i.e., stepwise regression and forecasting from statistically determined graphs.

The rationale of a stochastic-dynamic approach to numerical weather prediction deals with an initial uncertainty by considering an infinite ensemble of initial states in space-phase, with relative frequencies within the ensemble being proportional to probability densities [87]. The evolution of the ensemble in time, as given by the stochastic-dynamic equation set, is based upon the original deterministic hydrodynamic equation set.

Climatology has always formed an integral part of weather forecasting, having been used both subjectively and objectively in many ways. In numerical weather prediction, climatological statistics are used in obtaining the weighting functions in optimal interpolation objective analysis, and as the first guess in some iterative objective analysis techniques. In the tropics, climatology constitutes an important part of statistical forecasting and is even used in dynamical prediction models. In very short-range terminal forecasting, climatological records are the basis of the widely used station conditional probability tables.

Model Output Statistics Technique. Another method of obtaining objective forecasts of local weather elements involves the use of statistical models to complement the output of numerical prediction models. This is the Model Output Statistics (MOS) technique in which local observations of weather parameters are matched with output parameters from numerical models for a period of one year or more [88]. Forecast equations are then derived by statistical techniques that can account for biases and inaccuracies in the numerical model and local climatology. The MOS technique has been applied to forecasts of such weather elements as precipitation, clouds, thunderstorms, temperature, and wind [89].

The contributions of satellite meteorology to modern weather prediction are already substantial. Visible and infrared imagery data and radiometric atmospheric sounding data from satellites are currently being applied in numerical prediction models. Other remote sensing tools, i.e., Doppler radar and acoustic sounders, now offer interesting new possibilities for improved capability in the prediction of severe storms.

Forecasting of Precipitation

Precipitation is one of the most difficult weather elements to forecast, and numerical forecasts of precipitation have been the least useful of all outputs from numerical models. Weather forecasters still have to depend on personal skill and experience when making precipitation forecasts, particularly forecasts of precipitation amount. There is a seasonal variation of skill in manual quantitative precipitation forecasts dependent upon the predominant scale of precipitation systems, i.e., synoptic scale in the winter to the small mesoscale in the summer. It is more difficult to forecast the occurrence and distribution of precipitation with thunderstorms than with winter storms.

Availability of Physical and Dynamical Meteorological Information. A great deal of available physical and dynamical meteorological information has application in precipitation forecasting. Calculations of raindrop growth made with a parameterized updraft pattern, has shown that when the maximum drop diameter becomes 3 to 4 mm, rainfall can be expected to grow to 50 mm/hr [90]. Calculations of water content, as a function of the temperature of the cloud atmosphere and mean velocity of ascending air in the cloud, have predicted rain shower intensity computations with a correlation of approximately 0.80 to observed intensity values [91]. The concentration of cloud droplets, i.e., the number of nuclei active when maximum supersaturation is attained in a cloud, is the most sensitive factor in determining rainfall, and there is a critical drop size distribution for initiation of rain [92].

Mesoscale Effects on Precipitation. Precipitation intensity usually fluctuates with periods of 10-20 minutes and 2-6 hours, which are considered to be related to convective activity and mesoscale disturbances, respectively [93]. In many aspects, mesoscale disturbances have gravity wave characteristics; therefore, it is important to clarify the interaction between convective activity and mesoscale disturbances. Consequently, a Portable Automated Mesonet (PAM) was used to identify surface mesoscale circulations influencing thunderstorm development during the National Hail Research Experiment '76 [94]. PAM consists of a trailer-mounted base station and a network of remote sampling stations which sample surface mesoscale data synchronously. Data (pressure, temperature, humidity, rain, wind direction, and speed) are averaged locally and transmitted digitally via a telemetry link to the base station where real-time data from the entire network are displayed.

Furthermore, after about 20 years of big mesometeorology planning, but little systematic implementation, it appears that some dramatic advances are imminent. Plans are now being formulated for a special severe storm satellite, STORMSAT, for mesoscale coverage in the early 1980's, and the Severe Storms and Mesoscale Experiments, SESAME, will play a large role in providing scientific and observational support for understanding and modeling mesoscale phenomena and assessing their predictability [95].

Statistical Applications to Precipitation Forecasting. Rapidly developing hydrological research activities require more knowledge of statistically analyzed time series data of precipitation [96]. There has been increasing interest toward fitting a finite auto-regression to the time series data and estimating the variance of a time series by calculating the spectrum from the estimated auto-regression coefficients and the one-step predictor error variance [97]. Digital filters have become a prime tool for analyzing sampled time series, but the main problem in filter design is to obtain short operators with fairly accurate frequency characteristics [98].

The statistical distribution of rainfall amounts over relatively long periods (months, years) have received considerable attention in the past, but for moderate to small time intervals (weeks, days, hours)

satisfactory distributional models are more difficult to find [99].

The synoptic-statistical approach has been used to forecast floods and droughts in the tropics for periods ranging from one month to years. However, J. Namias, a US pioneer in extended range forecasting, has expressed a hope that more dynamical methods will be used in the future [100]. Properties of the Korean rainy season have been investigated statistically from the frequency of occurrence of a bad weather (climatic) index and the seasonal variation of the polar front [101].

A very recent example of the use of climatological data as applicable to hydrometeorology involved an investigation of heavy rainstorms in the Northern Illinois area [102]. Based on historical data of rainfall and associated weather conditions, frequency distributions of point rainfall were presented for rain periods ranging from 5 minutes to 72 hours and recurrence intervals of 6 months to 50 years. Also presented were the relationship between point and area mean rainfall frequencies, time and space distribution characteristics of heavy rains, orientation and movement of storms, the frequency distribution of storm centers, synoptic weather conditions associated with severe rainstorms, and the diurnal, monthly, and seasonal distribution of flood-producing storms.

A stochastic model has been developed to determine the cumulative distribution function of the total rainfall per event based upon a particular random structure of space-time rainfall [103]. Two random variables of the spatial rainfall, i.e., the cumulative rainfall within a season and the maximum cumulative rainfall per rainfall event within a season, were considered. One-minute and 4-minute precipitation rate records have also been used to develop stochastic model relations between clock hours and 1-minute (or 4-minute) precipitation rate distributions for use in estimating seasonal and annual distributions of instantaneous precipitation rates for locations where distributions of clock-hour rates are known.

Variational analysis of hourly observations has led to recognition of the importance of the planetary boundary layer in severe storm development. Vertical momentum transport, frictional convergence, and gravitational motion have been found to be associated with the formation of squall lines and thunderstorms. It has been found that in a barotropic atmosphere where convection is predominantly surface-forced, a high correlation exists between surface convergence and the predictability of rainfall.

<u>US National Meteorological Center Boundary Layer Model</u>. The NMC has experimented with a Planetary Boundary Layer (PBL) model (similar to the US Air Force Global Weather Central (GWC) operational model) which has eight levels between the surface and 1600 meters and a horizontal grid mesh of 190.5 km over the contiguous US [104]. Forecasts based on 0000 GMT data, utilizing all conventional data sources plus satellite input, were run to 2400 GMT; results showed that the model has potential for providing usable forecasts of rain versus snow delineation, cloud

ceiling, and areas of severe weather over the Eastern two-thirds of the US. However, the model did not perform well during the summer months and over the mountainous region.

Numerical quantitative precipitation forecasts have been computed as a function of the vertical velocity and humidity distribution in the atmosphere. The orographic influence on the vertical velocity and the relation between vertical velocity and static stability of the atmosphere, as an important factor in the condensation process, have been introduced into the forecast model [105].

The release of isolated summer showers has been related to influences of the urban heat island [106]. The forecasting of precipitation types, utilizing the 1000-500 mb thickness, has been enhanced significantly by also considering the mean lapse rate in that layer [107]. The total energy of instability in the 700-500 mb layer plays a fundamental role in the rain intensity process within cumuliform clouds [108].

Another technique was developed for utilizing existing series of satellite cloud photographs to estimate total daily precipitation (rain and snow) over a specific drainage basin (Flathead River, Montana) [109]. Basic data consisted of surface observations of daily precipitation over the climatological network and a series of one-per-day photographs (both as large-scale mosaics and individual frames) from polar orbiting satellites. A high correlation coefficient was obtained between estimated and observed precipitation amounts.

Precipitation Forecasting in Other Nations

a. Soviet Union

There has been much activity in the Soviet Union relating to precipitation forecasting. One operational model uses the equation of motion and the first law of thermodynamics to derive prognostic equations in a baroclinic atmosphere applicable to the short-range (48 hours) prediction of isobaric contour patterns and vertical velocity from which precipitation amount or intensity can be predicted. In another approach, the entry time for condensation and the quantity of combined water vapor for a given time interval are determined by calculating the derivatives of pressure and the initial values of temperature and moisture at different atmospheric levels [110]. Vertical velocities at 1 and 3 km heights are then calculated based on ground pressure charts. The quantity of condensed water vapor in an air column 6 km high over the time interval under consideration is expressed in millimeters of precipitation and used to forecast precipitation amounts for a period of 12 hours.

An integral circulation index which numerically evaluates the atmospheric circulation of the Northern Hemisphere has been used to forecast the formation of precipitation over Central Asia with a lead time up to 6 months [111]. Also, an equation which considers the influence of solar activity, types of atmospheric circulation, and a 2-year periodic-

ity in Northern Hemispheric circulation has allowed calculations of monthly and seasonal precipitation amounts over Western Asia with a claimed reliability of about 90% [112].

In 1975, the Soviet Union issued accuracy results of forecasting monthly precipitation totals in the past 10 years for regions of Kazakhstan. Forecasting accuracy of the measured monthly precipitation totals throughout the territory, and by seasons of the year, was distributed nonuniformly (from 54 to 80%) [113].

b. Other Techniques

Elsewhere, a numerical model which improves the original Bushby-Thompson 10-surface atmospheric model by more realistic considerations of such processes as friction between the atmosphere and the earth's surface and the vertical transport of heat and moisture to simulate clouds has been used successfully to predict precipitation distribution 24 hours in advance in the British Isles and Western Europe [114].

A Polish technique entails the use of statistical methods to analyze satellite TV cloud pictures [115]. Every cloud system on TV pictures is described by a five-digit word; thus, a definite digit in a definite place in the group describes a definite feature of the cloud system appearance. Using this method, it is possible to correlate cloud system appearances and precipitation phenomena; regions of rain and showers and their intensity changes up to 12 hours, and of thunderstorms up to 24 hours, from picture-taking time can be determined. Cloud system appearances may also be used as additional information in quantitative precipitation forecasts.

Thunderstorm Forecasting. Since its introduction to meteorology, radar has been used extensively to observe the formation and movement of thunderstorms. It is sometimes possible to accurately predict the passage of a widespread squall line of thunderstorms several hours in advance and the arrival time of an individual thunderstorm up to perhaps 20 minutes in advance, but usually these times are practical upper limits. In the prediction of thunderstorm paths, the possibility of the dissipation of existing storms or, more importantly, the development of new storms in the area ahead of existing storms must be considered [116].

a. US National Weather Service Approach

The Technical Development Laboratory (TDL), NWS, approach to the short-range forecasting (0-2 hours) of thunderstorms and severe weather places dependence upon digitized radar data to depict the intensity, movement, and evolution of severe weather systems, with pattern recognition techniques being used to isolate, track, and predict the movement of significant radar echoes [117].

TDL has also developed and implemented an objective method of 2-6 hour forecasting of the probability of thunderstorm occurrence within a square area, 40-45 nmi on a side [118]. The prediction scheme is based on a hybrid combination of the classical statistical and MOS approaches, with the probabilities being produced by multiple linear regression equations. The independent variables or predictors, e.g., wind components, mixing ratio, potential temperature advection, and stability indices, are derived from routinely observed surface atmospheric variables, manually digitized radar data, localized climatic frequencies of thunderstorms, and large-scale numerical model forecasts of basic upper-air variables. Over a short forecasting period (spring), forecasts of the climatic (statistical) frequency and persistence of thunderstorms showed considerable skill. Subjective examination of individual cases showed that the envelopes of high probability values matched well with the general patterns of thunderstorm occurrence.

The TDL approach to medium range forecasting (6-24 hours) of thunderstorms and severe weather involves the combining of dynamics and statistics with predictors generated from meteorological parameters obtained from NMC's 6-layer PE model and TDL's own 3-dimensional trajectory model. Using computed trajectories from wind forecasts by the NMC model, detailed 24-hour forecasts of temperature and dew point are derived by computing 6-hour variations of potential temperature and mixing ratio for air parcels assumed to follow paths defined by the trajectories.

The TDL trajectory model was recently modified to include surface land and ship reports and initialized grid-point values from the NMC six-layer PE model [119]. In the new analysis procedure, upper-air and PE data are assigned relative weights by means of a unique function that measures the asymmetry of the radiosonde station distribution at the initial position for each trajectory.

b. Other Methods of Forecasting Thunderstorms

Another objective technique has been developed for modifying 12- to 24-hour precipitation guidance forecasts from the NMC PE model by using manually digitized radar and the LFM model 12- to 24-hour precipitation forecasts [120]. Developmental data were from two stations in the Eastern US for the summer season. Constructed radar variables were entered into a stepwise multiple regression program with the PE precipitation probabilities and the LFM precipitation forecast. The resulting equation yielded subjective improvement over the PE guidance amounts by 10-15%.

In the objective forecasting of the probability of thunderstorm occurrence, recognized severe storm indicators have included the following: (1) hydrostatic quantities (e.g., Showalter Stability Index, moisture content, and a combined representation of the low-level temperature-dew point fields); (2) the effect of differential temperature advection between the low and mid troposphere; (3) kinematic quantities representing

the presence of an activating mechanism of potential instability (e.g., low level vorticity genesis); and (4) a destabilizing distribution of temperature advection between low and mid troposphere with the simultaneous presence of horizontal convergence in low levels and of horizontal divergence in the upper levels [121].

A Severe Weather Threat (SWEAT) Index for forecasting severe thunderstorms and tornadoes was developed at GWC. The index is empirical and based on the 850 mb dew point, sum of the 850 mb temperature and dew point minus twice the 500 mb temperature, speed of the 850 mb and 500 mb winds, and the directional shear between the 850 mb and 500 mb winds [122].

c. Sferics Technique

There is also some evidence that a technique for noting the occurrence of lightning discharges and their bearing from a station (sferics signals) can be used for thunderstorms and tornado identification. It has been observed that the frequency of sferics reaches a pronounced maximum prior to the formation of severe thunderstorms or tornadoes.

A transistorized lightning counter has been developed in the People's Republic of China and used for forecasting hailstorms. Simple in structure, easy to handle, and inexpensive, the instrument is suitable for use in both plains and mountain areas [123]. As described, when a mass of hail-producing clouds appears within 40 km from the instrument, its antenna will automatically transmit lightning-produced signals to the counter. A given number of recorded lightning signals indicates that a hailstorm is impending.

US National Hurricane Center. The HURRAN statistical model used at the US National Hurricane Center is based on all recorded past storms that: (a) occurred within a fixed number of days from an existing storm, (b) occurred within a certain distance from the storm (usually within 2.5° latitude), and (c) moved with similar speed and direction. This permits a stratification of hurricane climatology for use in forecasting and long-range planning [124].

Other purely statistical hurricane prediction models used by the US National Hurricane Center (NHC) include CLIPER, NHC 67, and NHC 72. A statistical-dynamical model is represented by NHC 73, while purely numerical models include the barotropic SANBAR and baroclinic Movable Fine-Mesh (MFM) model.

Many studies of the joint frequency of the initial and final conditions of weather elements, e.g., rainfall and cloud cover, attest to the importance of the initial event as a predictor of the later event [125]. By assuming the Markov process (in which the past history does not affect conditional probabilities of events defined in terms of the future) and a bivariate normal distribution, a two-parameter model was developed by US Air Force Researchers which charts the parameters as

direct functions of the probability of the initial event; the model can then be used to estimate conditional probabilities of both frequent and rare events.

Previous models for estimating the conditional probability of an event have used a categorized event as the initial condition, e.g., "no rain" or "overcast" at zero time. However, initial conditions frequently are known in detail and this model applies those detailed conditions in determining conditional probabilities [126].

Probability of Precipitation Forecasts. Probability of Precipitation (POP) values derived from estimates of the gamma probability function (as developed by Thorn) have been used to depict regional precipitation characteristics over the Eastern US, and indicate the importance of lake effects, sea breeze convergence, coastline geography, and proximity to storm paths in POP predictions [127].

Radar information has been used with synoptic and radiosonde data to produce more accurate short-term POP forecasts [128]. The radar provides details about area coverage, echo shape, number, size, orientation, and movement while nonradar parameter predictors include the mean relative humidity in the convective cloud layer, slice stability index, and subcloud water vapor capacity.

Regression techniques for obtaining POP over the Western US from 500-mb flow typing have represented a substantial improvement over climatology when the flow is significantly different than climatological [129]. In computing correlations between meteorological factors and snowfall, most statistical multiple regression equations appear as a combination of the predictor related with temperature producing heavy snow on the large scale and the predictor related with surface wind controlling the local distribution of snowfall [130].

Elevation, latitude, date, 850-mb temperature, 1000-500-mb thickness, and boundary layer temperature predictors have been used to produce objective (computer) POP predictions of snow, sleet, or freezing rain up to 48 hours [131].

Distinguishing variants of the disposition of pressure systems producing winter snowstorms, together with data of snowstorm frequency in specific regions of the Arctic during particular synoptic processes, have been used to make snowstorm probability forecasts with a lead time of 3-4 days [132].

Estimates of Probable Maximum Precipitation. Estimates of Probable Maximum Precipitation (PMP), or the greatest depth of precipitation for a given duration with no allowance made for long-term climatic trends, are based mainly on the traditional approach, i.e., moisture maximization and transposition of observed storms and consideration of elevation, moisture inflow barriers, and distance from the moisture source [133]. Procedures for estimating PMP vary with amount and quality of available

data, basin size and location, basic and regional topography, storm types, and climate.

Forecasting of Cloud Amount and Height

US Air Weather Service Models. Numerical methods have become a popular means of predicting fields of layered cloudiness. One of the better known mathematical formulations in cloud forecasting is the GWC model consisting of three modules, i.e., macroscale clouds (MSC), 5-layer (5 LYR), and high resolution cloud prog (HRCP) [134]. Forecasts are based upon three-dimensional parcel displacements computed from dynamic numerical prediction models. The most detailed HRCP produces a 3-, 6-, or 9-hour cloudiness forecast for 15 layers from the surface to 55 Kft at a 25 nmi grid interval covering the Northern Hemisphere. The other models produce less detailed cloudiness forecasts for periods up to 48 hours.

GWC also has an operationally useful convective parameterization technique applicable in numerical cloud forecasting [135]. This technique uses certain dynamic variables from the GWC data base and relates these variables to statistical convective activity through a nomogram. The amount of cumulus cloud cover is assumed to be a function of stability and the subcloud layer moisture convergence.

Other Techniques for Cloud Prediction. The MOS prediction technique treats cloud ceiling height both as a categorized and as a continuous predictand [136]. Where cloud ceiling height is categorized, the Regression Estimation of Even Probabilities (REEP) screening technique is used to develop probability forecast equations. Where ceiling height is treated as a continuous variable, specific ceiling height forecast equations are developed by ordinary screening regression. Forecasts from REEP equations are generally better than those based on specific height equations, climatology, and persistence.

The numerical six hourly output from the 6-layer NMC PE model has been used to predict average daytime cloudiness in spring [137]. Variables chosen as predictors were the PE model predictions of mean relative humidity between the surface and 500-mb, the 700-mb vertical velocity, and the relative humidity trend through a 12-hour period.

An objective method uses satellite data from the visible and IR window bands to derive current and 6-hour forecasts of cloud amounts and ceilings [138]. Visible data were carefully calibrated and normalized for solar elevation and bidirectional reflectance; and cloud motions were used for 6-hour forecasts. Data were reduced to values of average brightness and its standard deviation over 1/2 x 1/2° areas before analysis. Results have indicated a root mean square error for current cloud amounts (on a scale of 0 to 1) of about 0.25 and for 6-hour forecasts about 0.35. The occurrence of a ceiling (more than 0.5 coverage) or no ceiling was specified correctly for 80% and 70% of the time at 0 and 6 hours, respectively.

Qualitative estimates of the occurrence, persistence, and dispersal of low-level cloudiness over Asia were obtained by applying the fundamental factors of convergence, moisture, surface temperature variation, and nature of stratification in the lower 1.5 km layer of the atmosphere.

One- to two-hour forecasts of the variation in lower cloud boundary height have been made from data of the variation rate of the lower cloud boundary during the last observation period as determined by the Laplacian transformation of pressure, the temperature, and relative humidity at the ground and lower cloud boundary height [139].

Frequency distributions of cloud amounts, as described by simple linear equations, have also been used to estimate mean values of cloud cover.

Fog Forecasting. Enhanced IR satellite pictures have been suggested as a new tool for forecasting the extent of warm air advection fog and stratus formation [140]. Frequently areas in which fog and stratus are most likely to form will appear as relatively dark areas on the satellite pictures taken a few hours after sunset. These dark areas are found normally upwind from a moisture source and appear to outline the boundary of relatively moist air in lower levels of the atmosphere. This boundary can be monitored and used as an estimate of the extent of fog and stratus formation during the night. A method, quick enough for operational use, has also been developed for using satellite-observed cloud brightness to forecast fog and stratus dissipation [141].

A two-dimensional dynamical model has been developed to forecast fog for periods of up to 8 hours on a local scale [142]. Time-dependent winds are generated by calculating a stream function from a model-produced vorticity field, and a diurnal surface variation is simulated by sinusoidally varying the lower boundary conditions on temperature. Surface terrain effects can be incorporated into the model; however, fine-scale data are required and wind values are limited by an inability to include synoptic-scale variations.

Another fog forecasting method is based on the dependence of the relative frequency in occurrence of visibilities lower than 1000 meters upon the daily time, surface wind direction and speed, and the type of synoptic situation [143].

A simple method of forecasting fog at Praque, Czechoslovakia, is based upon the values of average temperature lapse in the layer between the ground and 850-mb level and the values of wind speed at the 900-mb level [144].

A conductive-radiative model has been used to predict the formation and growth of radiation fog by solving numerically the heat and mass transport equations in conjunction with an approximate form of the radiative transfer equation [145].

A technique developed in the Soviet Union for predicting fog formation intensity and duration is based upon mathematical determination of expected nocturnal variation of the specific humidity and nocturnal minimum temperature in the atmospheric surface boundary layer. Verification was claimed in 88% of about 160 cases in which fogs were noted during the night and weather conditions were favorable to fog formation.

Forecasting of Temperature, Humidity, and Wind Speed Profiles

Temperature Profile Forecasts. TDL, NWS, has under development a large-scale three-dimensional planetary boundary layer model to predict temperature, humidity, and winds in the lowest 2 km of the atmosphere [146]. The model, consisting of 12 levels within two layers (i.e., a 50-meter thick surface layer having constant fluxes of heat, momentum, and moisture and a transition layer extending to 2 km) has shown good agreement between the predicted and measured boundary layer temperatures and winds.

The Monin-Obukov log-linear model has been examined for adequacy in describing temperature and wind profiles in thermally stratified shear flows and diversified thermal stability [147]. The dimensionless wind shear and lapse rate for all ranges of thermal stability examined were shown to be linearly dependent upon the dimensionless height derived from the log-linear model.

The Galerkin method has also been used to numerically solve the nonlinear initial boundary value problem describing the vertical temperature profile for a thermally coupled soil-atmosphere boundary layer in a simple physical setting [148]. However, this numerical simulation requires special mathematical techniques for handling interior boundary or coupling conditions.

Humidity Profile Forecasts. Data from 11 widely dispersed geographical locations within the US have been sorted with respect to temperature intervals of 5° C and relative humidity intervals of 10% for the lowest 1400 meters of the atmosphere. These data have been assembled in a statistical format and classified into altitude increments of 200 meters for each site by season of the year [149].

Many mathematical descriptions have been presented for profiles of boundary layer air temperature and wind speed over various types of ground vegetation surrounded by irregular and inhomogeneous terrain [150]; while the humidity profile has been estimated by using an empirical formula linking changes in humidity with changes in temperature and altitude [151].

More accurate prognostic stratification curves of nighttime temperature and humidity have been constructed by taking into account the nonlinear temperature and humidity variations in the surface to 850-mb layer [152].

Wind Profile Forecasts. The generalized Ekman equation has often been used for micrometeorological determinations of the wind profile [153]. Both the eddy diffusivity and the thermal wind are important considerations when this equation is applicable.

It has been claimed that wind velocity variations with height can be described satisfactorily by the expression $V_Z = V_0 (Z/Z_0)^m$, where V_Z and V_0 are wind velocities at heights Z and Z_0, respectively, and m = 0.125 [154].

Comparisons have been made between tower-observed wind profiles and profiles predicted from models based on mixing-length theory and, in the case of a single roughness change, on the turbulent energy equation [155]. Comparisons with the mixing-length model are moderately good, but some features of the observed profiles are missing in the theoretical predictions. The turbulent energy equation model has given slightly less accurate wind profile predictions.

SUMMARY

The measurement and prediction of weather variables are of extreme importance to Army decision makers in tactical planning and operations. Weather changes can seriously affect weapons systems, target acquisition, and battlefield surveillance systems. Weather can also influence the deployment of smoke and chemicals and selection of air and ground mobility tactics.

Measurement Capabilities

Remote sensing is a relatively new tool for investigating the structure and dynamics of the atmosphere. It has significant applications to weather and severe storm forecasting, because it combines reasonably accurate data with spatial and temporal resolution (in essentially real time) over much larger volumes of the atmosphere than is possible by other means.

With the arrival of the meteorological satellite, a capability for complete global weather observations was realized. Visible and infrared images from polar-orbiting satellites now provide day and night surveillance of weather systems over the entire earth [156]. Geostationary satellites hovering over the equator now send data back to earth every half-hour for a substantial portion of the Western Hemisphere [157]. Moreover, the geostationary satellite has proved valuable as a means of indirectly providing data on winds in remote ocean areas through its ability to track cloud motions.

Radiometric methods have been developed for sounding the atmosphere from satellites. In addition to the IR sounders, which measure temperature and moisture profiles, experimental microwave sounders have been flown that are able to detect precipitation areas within large cloud masses.

Significant improvements have occurred in some areas of meteorology during the past 5 years. One particular example is the application of vertical temperature profile radiometer data to large-scale forecasting at the National Meteorological Center (NMC). However, routine applications of satellite data to mesoscale problems are still confined largely to visual and IR images of clouds, although quantitative radiometer data for the mesoscale remain on the verge of being used routinely.

The most useful ground-based remote techniques involve acoustics and radar. New operational uses of radars have not increased greatly since 1972, although Doppler radar techniques are progressing rapidly. Of all the surface-based remote techniques, the acoustic radar field has advanced most in terms of routine application.

A very good ground-based remote sensing capability exists for characterizing wind velocity because of the availability of a wide range of Doppler techniques. An all-weather, wind-profiling capability is attainable in the boundary layer, with prospects good for all-weather profiling to tropospheric heights, using some combination of microwave and IR Doppler systems.

The ability to remotely sense temperature and humidity is much poorer. It seems likely that it will be practical to measure temperature and humidity profiles, perhaps to tropospheric heights, within the next 6 years. However, it does not seem likely that remote measurement of the three-dimensional temperature and humidity fields will be available from ground-based remote sensors on this time scale.

The development of weather radar following World War II brought with it a belief that it would produce data with sufficient time and space resolution to accurately forecast severe thunderstorms. But, in spite of some fine technical developments, radar has not made the impact on severe weather forecasting that was expected. The basic problem lies in determining how severe the thunderstorm is at any given time, and how severe it will become in the following minutes or hours. Present-day operational radars of the US Weather Services, e.g., CPS-9, WSR-57, FPS-77, do not actually measure wind speed, hail size, or rainfall rate; rather, wind, rain, and hail have been related to radar return intensity, echo height, and echo development through empirical and theoretical studies.

Recent developments in electronics and data processing have simplified the task of obtaining quantitative data for estimating these meteorological parameters through the use of digital radar. Digital video techniques offer advantages for the digital processing of rainfall data for flood and trafficability forecasting. It is also suited for producing digitally integrated echo intensity contours of severe storms, and can be conveniently transmitted over land lines for remote display.

A difficult problem still remains in developing relationships between radar measurements and intense wind, rain, and hail due to the scarcity of meteorological measurements of such unusual events. Present weather

radars measure intensity and tops of clouds and thereby infer storm severity, whereas radar with a Doppler function can directly measure the phenomena (wind) that comprise the threat. Thus, parent circulations of tornadoes and gust fronts can be directly detected, measured, and predicted.

Forecasting Capabilities

Two technologies, Numerical Weather Prediction (NWP) and satellite meteorology have revolutionized meteorology in the past 20 years. Intermediate-range forecasts of 1-3 days are now made by NMC, while the very short-range forecast of 1-6 hours is becoming more impacted by satellite data as GOES pictures at 30-minute intervals become available in near real time. A merging of these technologies for making 6-18 hour forecasts through the use of mesoscale hydrodynamic numerical models is now envisioned with other tools (e.g., mesoclimatology studies based upon satellite and radar data, special-purpose simple models or forecast schemes, and empirical relations gained from forecaster experience and ingenuity) seen as important supplemental but important forecast aids.

Current numerical prediction model capabilities prove that significant progress has been made in the past 10-15 years in the forecasting of synoptic-scale weather features and weather parameters that can be derived from them, but the progress in forecasting precipitation and other small-scale weather elements has been much slower. Fine-mesh numerical models have resulted in improved forecasts of the location of precipitation areas, but important problems remain to be solved in the application of numerical techniques to the forecasting of smaller-scale weather phenomena, such as thunderstorms and heavy precipitation.

Although the impact of operational prediction models, from the barotropic to the primitive equations, has been most noticeable in construction of sea-level and 500-mb prognostic charts, progress in precipitation and cloud forecasting based on numerical weather prediction at the NMC has been modest [158].

Improvement in short-range (6-24 hours) forecasting accuracy is expected to continue at a deliberate, if not slow, rate [159]. However, it is not likely that POP forecasts will undergo any dramatic improvement in the foreseeable future [160]. Also, there are indications that the effect of truncation and other errors at the grid points of numerical models upon the exact timing of large-scale dynamics is very serious. This constitutes a formidable mathematical-physical computational problem which must be solved before accurate long-range weather predictions can be achieved [161]. It is very improbable that an operational forecasting ability will be attained within the foreseeable future for the prediction of seasonal mean atmospheric conditions for a year in advance [162].

On the large-scale, general circulation models have a role in studies of climatic processes but it has been difficult to develop models whose climatologies compare favorably with observed climatologies in any great

detail. Recognizing this problem, the World Weather Program has established a goal that would provide the data and knowledge needed to extend the range and accuracy of weather forecasts, particularly the prediction of climatic fluctuations and changes. This action is very timely in view of expert opinions, based upon recent climatological studies, which conclude that the world is now entering a period during which major climatic change is apt to take place with floods, hurricanes, droughts, tornadoes, killing frosts, and throttling snowstorms occurring far more often and randomly during the coming decades than ever before.

REFERENCES

1. Estes, J. E., and L. W. Senger, 1974, Remote Sensing: Techniques for Environmental Analysis, Hamilton Publishing Company, Santa Barbara, CA.

2. Derr, V. E. (ed.), 1972, "Remote Sensing of the Troposphere," Wave Propagation Laboratory, ERL, and Electrical Engineering Department, University of Colorado, Boulder, CO.

3. Piaget, A., 1974, "Meteorological Interpretation of High Image Resolution for Remote Sensing of Natural Resources," Symposium on European Earth-Resources Satellite Experiments, 28 January-1 February 1974, Frascati, Italy.

4. Mason, B. J., 1974, "Contributions of Satellites to the Exploration of the Global Atmosphere and to the Improvement of Weather Forecasting," Meteorol. Magazine, Bracknell, England.

5. Yates, H. W., 1972, "Remote Sensing from Satellites," Satellite Experiment Laboratory, National Environmental Satellite Service, NOAA, Washington, DC.

6. Oliver, V. J., and F. C. Parmenter, 1973, "Weather Forecasting with the Aid of Satellite Data," Applications Group, National Environmental Satellite Service, Washington, DC.

7. Meyer, W. D., 1973, "Data Acquisition and Processing Program: A Meteorological Data Source," Bull. Am. Meteorol. Soc., Vol. 54, No. 12, Boston, MA.

8. Blankenship, J. R., and R. C. Savage, 1974, "Electro-Optical Processing of DAPP Meteorological Satellite Data," Bull. Am. Meteorol. Soc., Vol. 55, No. 1, Boston, MA.

9. Hydrometeorological Centre, USSR, 1974, "The USSR Meteorological Satellite Programme."

10. Perez, D., and J. Armando, 1972, "Study on the Application of Radar for Meteorology," Recursos Hidraulicos, Mexico, D. F.

11. Battan, L. J., 1973, Radar Observation of the Atmosphere, The University of Chicago Press, Chicago and London.

12. Sirmans, D., 1972, "Digital Processing of Meteorological Radar Signals," Bureau of Meteorology, Melbourne (Australia), Meteorological Study No. 25.

13. Kawecki, A., 1971, "Radar Display of a Space Model of an Atmospheric Precipitation Intensity Distribution," Pański Instytut Hydrologiczno-Meteorologiczny, Prace (Poland), No. 102.

14. Woodley, W. L., et al., 1974, "Optimizing the Measurement of Convective Rainfall in Florida," NOAA, Environmental Research Laboratories, Technical Memorandum (NOAA TM ERL WMPO-18), Boulder, CO.

15. Treussart, H. et al., 1970, "Use of Weather Radar for Aviation," World Meteorological Organization, Technical Note No. 110, Geneva, Switzerland.

16. Puhakka, T., 1974, "On the Variability of the Z-R Relationship in Rainfall Related to Radar Echo Pattern," Geophysica Helsinki (Finland), 13(2).

17. Smith, P. L., Jr., 1973, "Weather Radar: Achievements, Promises, and Problems," Atmospheric Technology No. 2, Boulder, CO.

18. Senn, H. V., 1974, "Quantizing 3- and 5-cm Radar Hurricane Precipitation Data," University of Miami, School of Engineering and Environmental Design, Remote Sensing Laboratory, Contract No. 03-4-022-98, Final Report, Coral Gables, FL.

19. Grant, K., 1974, "Side Looking Radar Systems and Their Potential Application to Earth Resources Surveys, Part 1, Basic Physics and Technology," ELDO/ESRO Scientific and Technical Review, Vol, 6, No. 2, England.

20. Dombkovskaya, E., et al., 1974, "Meteorological Interpretation of Microwave Polarizational Satellite Measurements at 0.8 Region," 17th Plenary Meeting, COSPAR, San Paulo, Brazil.

21. Atlas, D., et al., 1973, "Doppler Radar Characteristics of Precipitation at Vertical Incidence," Reviews of Geophysical and Space Physics, 11(1), Washington, DC.

22. Kampwerth, D. H., and R. A. Rasmussen, 1974, "Verification of Rainfall Estimates: An analysis of Activation Patterns of ADSID and ACOUSID Seismic and Acoustic Intrusion Sensors to Determine Rainfall Rates," US Air Weather Service, Technical Report 253.

23. Shipley, S. T., et al., 1974, "Measurement of Rainfall Rates by Lidar," J. Appl. Meteorol., 13(7), Boston, MA.

24. Balin, Y. S., et al., 1974, "Lidar Investigations of Polarization Characteristics of Meteorological Formations," International Conference on Structure, Composition, and General Circulation of the Upper and Lower Atmospheres, and Possible Anthropogenic Perturbations," Vol. 1, 14-25 January 1974, Melbourne, Australia.

25. "ERL Scientists Use Lasers to Probe the Atmosphere," 1974, NOAA Week, 5(15), Rockville, MD.

26. Grams, G. W., and C. M. Wyman, 1972, "Compact Laser Radar for Remote Atmospheric Probing," J. Appl. Meteorol., 11(7), Boston, MA.

27. Fullerton, C. M., and D. J. Raymond, 1973, "Rainfall Intensity Instruments and Measurements," Water Resources Research Center, Technical Report No. 67, Honolulu, HI.

28. Drabble, J., 1975, "Measurement and Recording of Rainfall Intensities," Weather, 30(8), Bracknell, England.

29. Boardman, J., 1971, "Performane Testing of the Ground-Based and Snowflake Disdrometer Systems," Technical Operations, Inc., Report TO-B-714, Burlington, MA.

30. Langer, G., 1970, "Counter for Number of Snowflakes Falling Per Unit Area," Conference on Cloud Physics, 24-27 August 1970, Colorado State University, Fort Collins, CO.

31. Tusima, K., 1971, "Measurement of the Free Water Content of Wet Snow by the Volume Difference Method," Low Temperature Science, Ser. A, Physical Sciences, No. 29, Sopporo, Japan.

32. Bissell, V. C., and E. L. Peck, 1973, "Measurement of Snow at a Remote Site: Natural Radioactivity Technique," Symposium on Advanced Concepts and Techniques in the Study of Snow and Ice Resources, 2-6 December 1973, Monterey, CA.

33. Jones, E. B., 1973, "Areal Snowpack Water Equivalent Determinations Using Airborne Measurements of Passive Terrestrial Gamma Radiation," Symposium on Advanced Concepts and Techniques in the Study of Snow and Ice Resources, 2-6 December 1973, Monterey, CA.

34. Bissell, V. C., and Z. G. Burson, 1974, "Deep Snow Measurements Suggested Using Cosmic Radiation," Water Resources Research, 10(6), Washington, DC.

35. Byrd, R. C., et al., 1972, "Snow Measurement Using Millimetre Wavelengths," International Symposia on the Role of Snow and Ice in Hydrology, September 1972, Banff, Canada.

36. Meir, M. F., 1974, "Application of Remote-Sensing Techniques to the Study of Seasonal Snow Cover," J. Glaciol., 15(73), Cambridge, England.

37. Towery, N. G., et al., 1976, "A Review of Hail-Measuring Instruments," Bull. Am. Meteorol. Soc., Vol. 57, No. 9, Boston, MA.

38. Jameson, A. R., 1976, "Use of the Ratio of Radar Reflectivity Factors at 10- and 3-cm in Hailstorm Observations," 17th Radar Meteorology Conference, 26-29 October 1976, Seattle, WA.

39. Abrizzio, C., and A. Andressen, 1974, "Altitude Determination and Descriptive Analysis of Clouds on ERTS-1 Multispectral Photography," Symposium on Significant Results Obtained from the Earth Resources Technology Satellite-1, 10-14 December 1973, Washington, DC.

40. Tanczer, T., 1972, "Horizontal Extension of Cloud Systems Determined in Satellite Pictures," Idojaras, 76(5/6), September/December 1972, Budapest, Hungary.

41. Martin, D. W., and N. Dhirendra, 1975, "Case Study of Atlantic Cloud Clusters, Part 1, Morphology and Thermodynamic Structure," Monthly Weather Rev., 103(8), Boston, MA.

42. Reynolds, D., and T. H. Vonder Haar, 1973, "Comparison of Radar-Determined Cloud Height and Reflected Solar Radiance Measured from the Geosynchronous Satellite ATS-3," J. Appl. Meteorol., 12(6), Boston, MA.

43. Magnusson, L. S., 1975, "Automatic Cloud Amount Recorder," World Meteorological Organization, WMO No. 420, Geneva, Switzerland.

44. Tasso, L., and G. Benedicti, 1975, "Instrumental Evaluation of Cloudiness," World Meteorological Organization, WMO No. 420, Geneva, Switzerland.

45. Lenart, W., 1973, "Cloud Distribution over Small Areas Studied by the Method of Joining Photographs of the Whole Sky," Instytut Geografi, Prace i Studia: Klimatologia No. 7, Warsaw, Poland.

46. Bradley, J. T., and M. Leikowitz, 1975, "Experiments with New Generation Ceilometers for Potential Automatic Station Use," World Meteorological Organization, WMO No. 420, Geneva, Switzerland.

47. United States National Oceanic and Atmospheric Administration, National Weather Service, 1971, "Evaluation of Common Ceilometer Technology," Technical Memorandum (NOAA TM NWS T&EL), Washington, DC.

48. Naatz, O. W., 1970, "Method for Estimating Cloud Ceiling: Description, Application, Errors, Comparisons," Freie University Institut fur Meteorologie und Geophysik, Meteorologische Aghandlungen, 89(1), Berlin, Germany.

49. Katsurayama, (X) and (X) Yamanoto, 1972, "Some Experiments with Laser Radar," Toshiba Review, Vol. 27, No. 1, Kawasaki, Japan.

50. Zuev, V. E., et al., "Numerical Experiments on Laser Sounding of Mesospheric Clouds," Akademiya Nauk SSSR, Moscow.

51. Moroz, E. Y., and G. A. Travers, 1975, "Measurement of Cloud Height, Evaluation of Ranging and Triangulation Techniques for Determination of Cloud-Height at Airfield," US Air Force, Cambridge Research Laboratories, Air Force Surveys in Geophysics, No. 321, Bedford, MA.

52. Bonner, R. S., 1976, "The Application of a Laser Rangefinder to the Measurement of Ceiling and Visibility," 7th Technical Exchange Conference, 30 November-3 December 1976, El Paso, TX.

53. Garing, J. S., and B. Shurin, 1973, "Infrared Observations of the Earth's Upper Atmosphere," Astrophysics and Space Science Library, Vol. 35, Dordrecht, Holland.

54. Fleming, H. E., and W. L. Smith, 1972, "Inversion Techniques for Remote Sensing of Atmospheric Temperature Profiles," Instrument Society of America, Pittsburgh, PA.

55. Rodgers, C. D., 1973, "Infrared Remote Sounding," UCLA International Conference on Radiation and Remote Probing of the Atmosphere," 28-30 August 1973, Los Angeles, CA.

56. Gille, J. C., 1972, "Limb Scanning as a Method for Measuring the Temperature Structure of a Planetary Atmosphere," Instrument Society of America, Pittsburgh, PA.

57. Watson, J. K., and P. K. Yin, 1975, "Possibility of Atmospheric Temperature Sounding by the Solar Occultation Technique," Appl. Opt., 14(3), Washington, DC.

58. Wang, J. Y., and C. R. Claysmith, 1975, "Measurement of Lower Atmoshperic Temperature Profiles from Ground-Based Infrared Observations," J. Appl. Meteorol., 14(3), Boston, MA.

59. Miner, G. F., et al., 1972, "Inference of Atmospheric Temperature Profiles from Ground-Based Measurements of Microwave Emission from Atmospheric Oxygen," J. Geophys. Res., 77(6), Washington, DC.

60. Cooney, J., and M. Pina, 1976, "Laser Radar Measurements of Atmospheric Temperature Profiles by Use of Raman Rotational Backscatter," Appl. Opt., 15(3), Washington, DC.

61. Halsey, H. W., 1973, "Large Laser Radar for Atmospheric Probing," Society of Photo-Optical Instrumentation Engineers, Vol. 27, Redondo Beach, CA.

62. Mason, J. B., 1973, "Lidar Measurement of Temperature: A New Approach," R&D Report, ECOM-5506, US Army Electronics Command, Fort Monmouth, NJ.

63. Urin, B. M., 1973, "Possibility of Using a Combinational Scattering Effect for Measuring Atmospheric Temperature Altitude Distribution by Means of a Laser," Tsentral' naya Aerologicheskaya Observatoriya, Trudy, No. 105, Moscow.

64. Spizzichino, A., 1975, "Spectral Broadening of Acoustic and Radio Waves Scattered by Atmospheric Turbulance in the Case of Radar and Sodar Experiments," Ann. Geophys., 31(4), Paris, France.

65. Parry, H. D., 1973, "Remote Sensor of Atmospheric Temperature Profiles Usable under All Air Pollution Conditions," Instrument Society of America, Pittsburgh, PA.

66. Wyckoff, R. J., et al., 1973, "Comparison of the Low-Level Radiosonde and the Acoustic Echo Sounder for Monitoring Atmospheric Stability," J. Appl. Meteorol., 12(7), Boston, MA.

67. Strauch, R. G., et al., 1972, "Atmospheric Water Vapor Measurement by Raman Lidar," Remote Sensing of Environment, 2(2), New York.

68. Gething, J. T., and D. Jenssen, 1971, "Measurement of Temperature and Humidity by Acoustic Echo Sounding," Nature: Physical Science, 231(26), London.

69. Werner, C., 1973, "Possibility of Determining Relative Humidity by Lidar Measurements in the Atmosphere," Annalen der Meteorologie, No. 6, Offenbach, Germany.

70. Johnson, M. M., and A. H. LaGrone, 1973, "Determination of Atmospheric Water Vapor Densities from Measurements of the 6943.8-Å Absorption Line Strength," Radio Science, 8(5), Washington, DC.

71. Zamyshlya yev, I. V., et al., 1973, "Use of Laser Radiation for Humidity Profile Investigation in the Troposphere," Tsentral naya Aerologicheskaya Observatoriya, Trudy, No. 105, Moscow.

72. Wang, J. Y., 1974, "On the Estimation of Low-Altitude Water Vapor Profiles from Ground-Based Infrared Measurements," J. Atmospheric Sci., 31(2), Boston, MA.

73. Weiss, B. D., and J. F. Morrissey, 1972, "Investigation into Utilization of Loran and Omega Windfinding Systems for Measuring Winds Below an Aircraft," US Air Force Cambridge Research Laboratories, Instrumentation Papers, No. 177, Bedford, MA.

74. Simpson, R. H., and J. Simpson, 1975, "Implications from the GATE Dropwindsonde Program Regarding A-Scale Circulation," Global Atmospheric Research Programme, GATE Report No. 14, Vol. 1.

75. McGovern, W. E., 1975, "'NEXAIR' Upper Air Sounding System," US NOAA, Environmental Research Laboratories, Boulder, CO.

76. Kaufman, J. W., and M. Susko, 1971, "Review of Special Detailed Wind and Temperature Profile Measurements," J. Geophys. Res., 76(27), Washington DC.

77. Camp, D. W., and W. W. Vaughan, 1975, "High Resolution System for Tropospheric Wind and Temperature Profile Measurements," J. Geophys. Res., 80(27), Washington, DC.

78. Gage, K. S., and W. H. Jasperson, 1975, "Control Data Corporation's METRAC Positioning System," US NOAA, Environmental Research Laboratories, Boulder, CO.

79. Lalley, V. E., and R. M. Passi, 1975, "Wind Measurement Capabilities of a Doppler Radiosonde System (the Safesonde)," Monthly Weather Rev., 103(1), Boston, MA.

80. Chadwick, R. B., et al., 1976, "A New Radar for Measuring Winds," Bull. Am. Meteorol. Soc., Vol. 57, No. 9, Boston, MA.

81. Little, C. G., 1976, "Status Report on Ground-Based Remote Sensing of the Atmosphere," 7th Technical Exchange Conference, 30 November-3 December 1976, El Paso, TX.

82. Csaszar, M., 1974, "Energetic Activity of a Barotropic Atmosphere," Idojaras, 78(2), Budapest, Hungary.

83. Global Atmospheric Research Programme, 1974, "Modelling for the First GARP Global Experiment," GARP Publication Series, No. 14, World Meteorological Organization, Geneva, Switzerland.

84. Fuks-Rabinovich, M. S., 1974, "Effective Semi-Implicit Methods for Integration of a System of Prognostic Equations," Meteorology and Hydrology, No. 11, Washington, DC.

85. Fawcett, E. B., 1977, "Current Capabilities in Prediction at the National Weather Service's National Meteorological Center," Bull. Am. Meteorol. Soc., Vol. 58, No. 2, Boston, MA.

86. Julian, P. R., and A. H. Murphy, 1972, "Probability and Statistics in Meteorology: A Review of Some Recent Developments," Bull. Am. Meteorol. Soc., 53(10), Boston, MA.

87. Fleming, R. J., 1971, "On Stochastic Dynamic Prediction Part 2, Predictability and Utility," Monthly Weather Rev., 99(12), Washington, DC.

88. Glahn, H. R., and D. Lowry, 1972, "Use of Model Output Statistics (MOS) in Objective Weather Forecasting," J. Appl. Meteorol., 11(8), Boston, MA.

89. Bermowitz, R. J., 1975, "Application of Model Output Statistics to Forecasting Quantitative Precipitation," Monthly Weather Rev., 103(2), Boston, MA.

90. Fujiwara, M., et al., 1974, "On the Cloud Structure Related to Heavy Rainfall as Revealed by Radar," Papers on Meteorology and Geophysics, 25(1), Tokya.

91. Livanova, N. A., 1973, "Calculation of the Maximum Value of Precipitation Intensity over an Area 100 km in Radius," Dalnevostochnyy Nauchno-Issledovatel Skiy Gidrometeorologicheskiy Institut, Trudy, No. 38, Vladivostok.

92. Takhashi, T., 1975, "Rain from Shallow Convective Clouds, Maritime and Continental," Pure and Applied Geophysics, Vol. 113(5/6), Basel, Switzerland.

93. Matsumoto, S., 1974, "Mesometeorological Aspect of Precipitation," Journal de Recherches Atmospheriques, 8(1/2), Clermont-Ferrand, France.

94. Brock, F. V., and P. K. Govind, 1977, "Portable Automated Mesonet in Operations," J. Appl. Meteorol., Vol. 16, No. 3, Boston, MA.

95. Kreitzberg, C. W., 1976, "Interactive Applications of Satellite Observations and Mesoscale Numerical Models," Bull. Am. Meteorol. Soc., Vol. 57, No. 6, Boston, MA.

96. Salamin, A., 1974, "Analysis of Precipitation Series of Random Character," Idojaras, 78(3), Budapest, Hungary.

97. Jones, R. H., 1973, "Autoregressive Spectrum Estimation," 3rd Conference on Probability and Statistics in Atmospheric Science, 19-22 June 1973, Boulder, CO.

98. DeMeyer, F., and J. Van Isacker, 1975, "Synthesis of High Resolution Digital Filters," Institut Royal Meteorologique, Publications, Series A, No. 90, Brussels, Belgium.

99. Skees, P. M., and L. R. Shenton, 1974, "Comments on the Statistical Distribution of Rainfall Per Period under Various Transformations," US Agricultural Research Service, Miscellaneous Publication No. 1275, Washington, DC.

100. Namias, J., 1974, "Suggestions for Research Leading to Long-Range Precipitation Forecasting for the Tropics," International Tropical Meteorology Meeting, 31 January-7 February 1974, Nairobi, Kenya.

101. Lee, B., 1974, "Synoptic Study of the Early Summer and Autumn Rainy Season in Korea and in East Asia," Metropolitan University, Geographical Reports, No. 9, Tokyo.

102. Huff, F. A., and J. L. Vogel, 1976, "Hydrometeorology of Heavy Rainstorms in Chicago and Northeastern Illinois, Phase 1, Historical Studies," Illinois State Water Survey, Urbana, IL.

103. Gupta, V. K., 1973, "Stochastic Approach to Space-Time Modeling of Rainfall," University of Arizona, Technical Reports on Natural Resource Systems, No. 18, Tucson, AZ.

104. Polger, P. D., 1974, "Evaluation of the National Meteorological Center's Experimental Boundary Layer Model," US NOAA, National Weather Service, Technical Memorandum (NOAA TM NWS NMC-55), Washington, DC.

105. Radinovic, D., 1972, "Numerical Model for Quantitiative Precipitation Forecasting," Pure and Applied Geophysics, Vol. 93, Basel, Switzerland.

106. Harnack, R. P., and H. E. Landsberg, 1975, "Selected Cases of Convective Precipitation Caused by the Metropolitan Area of Washington, DC," J. Appl. Meteorol., 14(6), Boston, MA.

107. Weitz, T. J., 1972, "Paradox Principle in the Prediction of Precipitation Type," NOAA, National Weather Service Technical Memorandum (NOAA TM NWS WR72), Washington, DC.

108. Stanchev, K., et al., 1974, "On the Thermodynamic Criteria for the Intensity of Convective Cloud Development," World Meteorological Organization, WMO No. 399, Geneva, Switzerland.

109. Davis, P. A., and S. M. Serebreny, 1973, "Satellite Data and Estimates of Precipitation for Hydrologic Applications," Society of Photo-Optical Instrumentation Engineers, Vol. 27, Redondo Beach, CA.

110. Buleyev, N., 1973, "Estimation and Forecast of the Amount of Precipitation," Trudy Gidrometeorologicheskogo Nauchno-Issledovatelskogo Tsentra SSSR, No. 121, Moscow.

111. Aksarin, N. N., 1973, "Long-Term Forecasting of River Runoff and Precipitation for Central Asia by the Integral Index of Atmospheric Circulation Sredneaziatskiy Regional nyy," Nauchno-Issledovatel skiy Gidrometeorologicheskiy Institut, Trudy, 3(84), Tashkent, USSR.

112. Baydal, M. K., 1970, "Structure Analysis and Prediction of Climate Variations," Nauchno-Issledovatel'skiy Gidrometeorologicheskiy Institut, Trudy, No. 36, Alma-Ata, Kazakhstan, USSR.

113. Baydal, M., and A. Kuzmina, 1975, "The Territorial Distribution of Justification for Predicting the Monthly Amount of Rainfall for Kazakhstan," Kazakhskogo Ni Gidrometeorul Institut, Trudy, No. 46, Leningrad.

114. Gadd, A. J., 1971, "Precipitation Prediction by Computer," Die Umschau, 71(16), Frankfurt, West Germany.

115. Bunsch-Makarewicz, Z., 1973, "The Method of the Analysis of TV Satellite Pictures of Cloudiness and Its Application to Weather Phenomena Analysis and Forecasting," International Symposium on Meteorological Satellites, Paris, France.

116. Austin, G. L., and A. Bellon, 1974, "Use of Digital Weather Radar Records for Short-Term Precipitation Forecasting," Quart. J. Roy. Meteorol. Soc., 100(426), Bracknell, England.

117. Alaka, M. A., et al., 1973, "Objective Techniques for Forecasting Thunderstorms and Severe Weather," US Federal Aviation Administration, Report FAA-RD-73-117, Washington, DC.

118. Charba, J. P., 1977, "Operational System for Predicting Thunderstorms Two to Six Hours in Advance," US NOAA, National Weather Service, Technical Memorandum (NWS TDL-64), Washington, DC.

119. Reap, R. M., 1976, "Assimilation of Surface, Upper Air, and Grid-point Data in the Objective Analysis Procedure for a Three-Dimensional Trajectory Model," US NOAA, National Weather Service, Technical Memorandum (NOAA TM NWS TDL-59), Washington, DC.

120. Gilhousen, D. B., 1976, "Improving Short-Range Precipitation Guidance during the Summer Months," US NOAA, National Weather Service, Technical Memorandum (NOAA TM NWS ER-61), Garden City, NY.

121. Gotz, G., and G. Szalay, 1971, "Computer Technique for the Objective Analysis of Environmental Conditions Associated with Convective Processes," Idojaras, 75(1/2), Budapest, Hungary.

122. Bidner, A., 1971, "AFGWC Severe Weather Threat (SWEAT) Index: (A Preliminary Report)," US Air Weather Service Technical Report 242, Offutt AFB, NB.

123. Lanchow Institute of Highland Atmospheric Physics, 1974, "New Instrument for Forecasting Hailstorms," Survey of People's Republic of China Press, Hong Kong.

124. Hope, J. R., and C. J. Neumann, 1971, "Computer Methods Applied to Atlantic Area Tropical Storm and Hurricane Climatology," Mariners Weather Log, 15(5), Washington, DC.

125. Gringorten, I. I., 1971, "Modelling Conditional Probability," J. Appl. Meteorol.,10(4), Boston, MA.

126. Gringorten, I. I., 1972, "Conditional Probability for an Exact Non-categorized Initial Condition," Monthly Weather Rev., 100(11), Washington, DC.

127. Eichenlaub, V. L., et al., 1971, "Precipitation Probabilities as Indices of Climatic Variation over the Eastern United States," Professional Geographer, 23(4), Washington, DC.

128. Myers, J. N., 1973, "An Objective Procedure for Forecasting Short-Term Rain Probabilities in Air Mass Shower Situations," Thesis (Ph.D.), Pennsylvania State University, University Park, PA.

129. Paegle, J. N., 1974, "Prediction of Precipitation Probability Based on the 500 mb Flow Types," J. Appl. Meteorol., 13(2), Boston, MA.

130. Ishihara, K., 1971, "Study of Statistical Forecasting of Snowfall for Small Areas," International Symposium on Probability and Statistics in the Atmospheric Sciences, 1-4 June 1971, Honolulu, HI.

131. Bocchieri, J. R., and H. R. Glahn, 1973, "Computer Prediction of the Probability of Snow," Weatherwise, 26(6), Boston, MA.

132. Panchugin, R. G., 1972, "General and Downwind Snowstorms in the Arctic," Arkticheskiy i Antarkticheskiy Nauchno-Issledovatel' Skiy Institut, Trudy, Vol. 313, Leningrad.

133. World Meteorological Organization, 1973, "Manual for Estimation of Probable Maximum Precipitation," Operational Hydrology Report No. 1, WMO No. 332, Geneva, Switzerland.

134. Collins, R. W., 1970, "AFGWC Multilevel Cloud Model," US Air Force Global Weather Central, AFGWC Technical Memorandum 70-10, Offutt AFB, NB.

135. Hassebrock, A. W., 1973, "Parameterization of Convective Activity in a Macroscale Numerical Cloud Forecast Model," 8th Conference on Severe Local Storms, 15-17 October 1973, Denver, CO.

136. Bocchieri, J. R., and H. R. Glahn, 1972, "Use of Model Output Statistics for Predicting Ceiling Height," Monthly Weather Rev., 100(12), Washington, DC.

137. Sims, J. R., 1973, "Objective Method of Preparing Cloud Cover Forecasts," J. Appl. Meteorol., 12(4), Boston, MA.

138. Conover, J. H., 1975, "Specification of Current and Future Cloud Amounts and Ceilings from Satellite Data," US Air Force, Cambridge Research Laboratories, Air Force Surveys in Geophysics, No. 334, Bedford, MA.

139. Tkachenko, A. V., 1971, "One to Two Hour Forecasting of the Sign of Variation of the Height of the Lower Boundary of Low Clouds," Nauchno-Issledovatel' Skiy Gidrometeorologicheskiy Institut, Trudy, No. 106, Kiev, Ukraine.

140. Gurka, J., 1976, "Using Satellite Data as an Aid to Forecasting Fog and Stratus Formation," US National Weather Service, National Environmental Satellite Service, Satellite Applications Information, Note 3/76-1, Washington, DC.

141. Gurka, J., 1974, "Using Satellite Data for Forecasting Fog and Stratus Dissipation," 5th Conference on Weather Forecasting and Analysis, American Meteorological Society, Boston, MA.

142. Doswell, C. A., III, 1972, "Two-Dimensional Short-Range Fog Forecast Model," R&D Report, ECOM-5443, US Army Electronics Command, Fort Monmouth, NJ.

143. Novak, Z., 1973, "Forecasting Poor Visibility at Ruzyne Airport in Prague," Meteorologicke Zpravy, 26(2), Prague, Czechoslovakia.

144. Novak, Z., 1976, "Results of the Analysis of Some Fog Situations at the Ruzyne Airport, Prague," Meteorologicke Zpravy, 29(1), Prague, Czechoslovakia.

145. Zdunkowski, W. G., 1972, "Radiative-Conductive Model for the Prediction of Radiation Fog," Boundary Layer Meteorology, 3(2), Dordrecht, Holland.

146. Schaffer, W. A., and P. E. Long, Jr., 1975, "Predictive Boundary Layer Model," US National Weather Service, Technical Memorandum (NOAA TM NWS TDL-57), Washington, DC.

147. Chuang, H., and J. E. Cermak, 1969, "The Diabatic Wind and Temperature Profiles," Fluid Dynamics and Diffusion Laboratory, Colorado State University, Fort Collins, CO.

148. Garder, A., and W. H. Raymond, 1974, "Galerkin Approximations to Vertical Temperature Profiles Across the Earth's Surface," Monthly Weather Rev., 102(6), Boston, MA.

149. Conner, A. B., et al., 1975, "Low Altitude Temperature and Humidity Profile Data for Application to Aircraft Noise Propagation," US National Aeronautics and Space Administration, Technical Note D-7975, Washington, DC.

150. Schneider, T., 1971, "Wind Profiles and Heat Transfer above a Short Grass Surface Surrounded by Irregular Terrain," Arch. Meteorol. Geophys. Bioklimatol., Ser. B 19(3), Vienna, Austria.

151. Bazlova, T. I., 1974, "Reconstructing the Vertical Profile of Humidity on the Basis of the Vertical Profile of Temperature," US National Aeronautics and Space Administration, Technical Translation F-801, Washington, DC.

152. Yakovleva, L. P. 1972, "Calculating the Amount of Precipitation for Heavy Rains Using More Accurate Curves for Temperature and Humidity," Meteorology and Hydrology, No. 5, Washington, DC.

153. Schaefer, J. T., 1973, "On the Solution of the Generalized Ekman Equation," Monthly Weather Rev., 101(6), Washington, DC.

154. Zavarina, M. V., 1973, "Profile of Calculated Wind Velocities and Wind Pressures," Glavnaya Geofizicheskaya Observatoriya, Trudy, No. 303, Leningrad.

155. Peterson, E. L., and P. A. Taylor, 1973, "Some Comparisons between Observed Wind Profiles at Riso and Theoretical Predictions for Flow over Inhomogeneous Terrain," Quart. J. Roy. Meteorol. Soc., 99(420), Bracknell, England.

156. LaViolette, P. E., et al., 1972, "New Satellites Offer Great Potential for Ocean Data Collection," Under Sea Technology, 13(11), Arlington, VA.

157. Vaeth, J. G., 1972, "Geostationary Environmental Satellites," Spaceflight, 14(10), London.

158. Brown, H. E., and E. B. Fawcett, 1972, "Use of Numerical Guidance at the National Weather Service's National Meteorological Center," J. Appl. Meteorol., 11(8), Boston, MA.

159. Cressman, G. P., 1970, "Public Forecasting: Present and Future," in: "A Century of Weather Progress," American Meteorological Society, Boston, MA.

160. Cummings, A. D., 1975, "Some Aspects of POP Forecast Performance by Southern Region WSFOs - Revisited," US NOAA National Weather Service, Technical Memorandum (NOAA TM NWS SR77), Fort Worth, TX.

161. Searle, J. W., and D. R. Davies, 1975, "Note on the Effect of Gridpoint Numerical Errors on the Large-Scale Flow Characteristics of a Four-Level Model of the Atmosphere," Tellus, 27(2), Stockholm, Sweden.

162. Laurmann, J. A., 1975, "On the Prospects for Seasonal Climate Forecasting," Bull. Am. Meteorol. Soc., 56(10), Boston, MA.

DISTRIBUTION LIST

Director
US Army Ballistic Research Laboratory
ATTN: DRDAR-BLB, Dr. G. E. Keller
Aberdeen Proving Ground, MD 21005

Air Force Weapons Laboratory
ATTN: Technical Library (SUL)
Kirtland AFB, NM 87117

Commander
Headquarters, Fort Huachuca
ATTN: Tech Ref Div
Fort Huachuca, AZ 85613

6585 TG/WE
Holloman AFB, NM 88330

Commandant
US Army Field Artillery School
ATTN: Morris Swett Tech Library
Fort Sill, OK 73503

Commandant
USAFAS
ATTN: ATSF-CD-MT (Mr. Farmer)
Fort Sill, OK 73503

Director
US Army Engr Waterways Exper Sta
ATTN: Library Branch
Vicksburg, MS 39180

Commander
US Army Electronics Command
ATTN: DRSEL-CT-S (Dr. Swingle)
Fort Monmouth, NJ 07703
03

CPT Hugh Albers, Exec Sec
Interdept Committee on Atmos Sci
Fed Council for Sci & Tech
National Sci Foundation
Washington, DC 20550

Inge Dirmhirn, Professor
Utah State University, UMC 48
Logan, UT 84322

HQDA (DAEN-RDM/Dr. De Percin)
Forrestal Bldg
Washington, DC 20314

Commander
US Army Aviation Center
ATTN: ATZQ-D-MA
Fort Rucker, AL 36362

CO, USA Foreign Sci & Tech Center
ATTN: DRXST-ISI
220 7th Street, NE
Charlottesville, VA 22901

Director
USAE Waterways Experiment Station
ATTN: Library
PO Box 631
Vicksburg, MS 39180

US Army Research Office
ATTN: DRXRO-IP
PO Box 12211
Research Triangle Park, NC 27709

Mr. William A. Main
USDA Forest Service
1407 S. Harrison Road
East Lansing, MI 48823

Library-R-51-Tech Reports
Environmental Research Labs
NOAA
Boulder, CO 80302

Commander
US Army Dugway Proving Ground
ATTN: MT-S
Dugway, UT 84022

HQ, ESD/DRI/S-22
Hanscom AFB
MA 01731

Head, Atmospheric Rsch Section
National Science Foundation
1800 G. Street, NW
Washington, DC 20550

Office, Asst Sec Army (R&D)
ATTN: Dep for Science & Tech
HQ, Department of the Army
Washington, DC 20310

Commander
US Army Satellite Comm Agc
ATTN: DRCPM-SC-3
Fort Monmouth, NJ 07703

Sylvania Elec Sys Western Div
ATTN: Technical Reports Library
PO Box 205
Mountain View, CA 94040

William Peterson
Research Association
Utah State University, UNC 48
Logan, UT 84322

Defense Communications Agency
Technical Library Center
Code 205
Washington, DC 20305

Dr. A. D. Belmont
Research Division
PO Box 1249
Control Data Corp
Minneapolis, MN 55440

Commander
US Army Electronics Command
ATTN: DRSEL-WL-D1
Fort Monmouth, NJ 07703

Commander
ATTN: DRSEL-VL-D
Fort Monmouth, NJ 07703

Meteorologist in Charge
Kwajalein Missile Range
PO Box 67
APO
San Francisco, CA 96555

The Library of Congress
ATTN: Exchange & Gift Div
Washington, DC 20540
2

US Army Liaison Office
MIT-Lincoln Lab, Library A-082
PO Box 73
Lexington, MA 02173

Dir National Security Agency
ATTN: TDL (C513)
Fort George G. Meade, MD 20755

Director, Systems R&D Service
Federal Aviation Administration
ATTN: ARD-54
2100 Second Street, SW
Washington, DC 20590

Commander
US Army Missile Command
ATTN: DRSMI-RRA, Bldg 7770
Redstone Arsenal, AL 35809

Dir of Dev & Engr
Defense Systems Div
ATTN: SAREA-DE-DDR
H. Tannenbaum
Edgewood Arsenal, APG, MD 21010

Naval Surface Weapons Center
Technical Library & Information
Services Division
White Oak, Silver Spring, MD
20910

Dr. Frank D. Eaton
PO Box 3038
Universtiy Station
Laramie, Wyoming 82071

Rome Air Development Center
ATTN: Documents Library
TILD (Bette Smith)
Griffiss Air Force Base, NY 13441

National Weather Service
National Meteorological Center
World Weather Bldg - 5200 Auth Rd
ATTN: Mr. Quiroz
Washington, DC 20233

USAFETAC/CB (Stop 825)
Scott AFB
IL 62225

Director
Defense Nuclear Agency
ATTN: Tech Library
Washington, DC 20305

Director
Development Center MCDEC
ATTN: Firepower Division
Quantico, VA 22134

Environmental Protection Agency
Meteorology Laboratory
Research Triangle Park, NC
27711

Commander
US Army Electronics Command
ATTN: DRSEL-GG-TD
Fort Monmouth, NJ 07703

Commander
US Army Ballistic Rsch Labs
ATTN: DRXBR-IB
APG, MD 21005

Dir, US Naval Research Lab
Code 5530
Washington, DC 20375

Mil Assistant for
Environmental Sciences
DAD (E & LS), 3D129
The Pentagon
Washington, DC 20301

The Environmental Rsch
Institute of MI
ATTN: IRIA Library
PO Box 618
Ann Arbor, MI 48107

Armament Dev & Test Center
ADTC (DLOSL)
Eglin AFB, Florida 32542

Range Commanders Council
ATTN: Mr. Hixon
PMTC Code 3252
Pacific Missile Test Center
Point Mugu, CA 93042

Commander
Eustis Directorate
US Army Air Mobility R&D Lab
ATTN: Technical Library
Fort Eustis, VA 23604

Commander
Frankford Arsenal
ATTN: SARFA-FCD-O, Bldg 201-2
Bridge & Tarcony Sts
Philadelphia, PA 19137

Director, Naval Oceanography and
Meteorology
National Space Technology Laboratories
Bay St Louis, MS 39529

Commander
US Army Electronics Command
ATTN: DRSEL-CT-S
Fort Monmouth, NJ 07703

Commander
USA Cold Regions Test Center
ATTN: STECR-OP-PM
APO Seattle 98733

Redstone Scientific Information Center
ATTN: DRDMI-TBD
US Army Missile Res & Dev Command
Redstone Arsenal, AL 35809

Commander
AFWL/WE
Kirtland AFB, NM 87117

Naval Surface Weapons Center
Code DT-22 (Ms. Greeley)
Dahlgren, VA 22448

Commander
Naval Ocean Systems Center
ATTN: Research Library
San Diego, CA 92152

Commander
US Army INSCOM
ATTN: IARDA-OS
Arlington Hall Station
Arlington, VA 22212

Commandant
US Army Field Artillery School
ATTN: ATSF-CF-R
Fort Sill, OK 73503

Commander and Director
US Army Engineer Topographic Labs
ETL-GS-AC
Fort Belvoir, VA 22060

Technical Processes Br-D823
NOAA, Lib & Info Serv Div
6009 Executive Blvd
Rockville, MD 20852

Commander
US Army Missile Research
and Development Command
ATTN: DRDMI-CGA, B. W. Fowler
Redstone Arsenal, AL 35809

Commanding Officer
US Army Armament Rsch & Dev Com
ATTN: DRDAR-TSS #59
Dover, NJ 07801

Air Force Cambridge Rsch Labs
ATTN: LCB (A. S. Carten, Jr.)
Hanscom AFB
Bedford, MA 01731

National Center for Atmos Res
NCAR Library
PO Box 3000
Boulder, CO 80307

Air Force Geophysics Laboratory
ATTN: LYD
Hanscom AFB
Bedford, MA 01731

Chief, Atmospheric Sciences Division
Code ES-81
NASA
Marshall Space Flight Center, AL 35812

Department of the Air Force
OL-C, 5WW
Fort Monroe, VA 23651

Commander
US Army Missile Rsch & Dev Com
ATTN: DRDMI-TR
Redstone Arsenal, AL 35809

Meteorology Laboratory
AFGL/LY
Hanscom AFB, MA 01731

Director CFD
US Army Field Artillery School
ATTN: Met Division
Fort Sill, OK 73503

Naval Weapons Center (Code 3173)
ATTN: Dr. A. Shlanta
China Lake, CA 93555

Director
Atmospheric Physics & Chem Lab
Code R31, NOAA
Department of Commerce
Boulder, CO 80302

Department of the Air Force
5 WW/DN
Langley AFB, VA 23665

Commander
US Army Intelligence Center and School
ATTN: ATSI-CD-MD
Fort Huachuca, AZ 85613

Dr. John L. Walsh
Code 4109
Navy Research Lab
Washington, DC 20375

Director
US Army Armament Rsch & Dev Com
Chemical Systems Laboratory
ATTN: DRDAR-CLJ-I
Aberdeen Proving Ground, MD 21010

R. B. Girardo
Bureau of Reclamation
E&R Center, Code 1220
Denver Federal Center, Bldg 67
Denver, CO 80225

Commander
US Army Missile Command
ATTN: DRDMI-TEM
Redstone Arsenal, AL 35809

Commander
US Army Tropic Test Center
ATTN: STETC-MO (Tech Library)
APO New York 09827

Commanding Officer
Naval Research Laboratory
Code 2627
Washington, DC 20375

Defense Documentation Center
ATTN: DDC-TCA
Cameron Station (Bldg 5)
Alexandria, Virginia 22314
12

Commander
US Army Test and Evaluation Command
ATTN: Technical Library
White Sands Missile Range, NM 88002

US Army Nuclear Agency
ATTN: MONA-WE
Fort Belvoir, VA 22060

Commander
US Army Proving Ground
ATTN: Technical Library
Bldg 2100
Yuma, AZ 85364

Office, Asst Sec Army (R&D)
ATTN: Dep for Science & Tech
HQ, Department of the Army
Washington, DC 20310

ATMOSPHERIC SCIENCES RESEARCH PAPERS

1. Lindberg, J.D., "An Improvement to a Method for Measuring the Absorption Coefficient of Atmospheric Dust and other Strongly Absorbing Powders, " ECOM-5565, July 1975.
2. Avara, Elton, P., "Mesoscale Wind Shears Derived from Thermal Winds," ECOM-5566, July 1975.
3. Gomez, Richard B., and Joseph H. Pierluissi, "Incomplete Gamma Function Approximation for King's Strong-Line Transmittance Model," ECOM-5567, July 1975.
4. Blanco, A.J., and B.F. Engebos, "Ballistic Wind Weighting Functions for Tank Projectiles," ECOM-5568, August 1975.
5. Taylor, Fredrick J., Jack Smith, and Thomas H. Pries, "Crosswind Measurements through Pattern Recognition Techniques," ECOM-5569, July 1975.
6. Walters, D.L., "Crosswind Weighting Functions for Direct-Fire Projectiles," ECOM-5570, August 1975.
7. Duncan, Louis D., "An Improved Algorithm for the Iterated Minimal Information Solution for Remote Sounding of Temperature," ECOM-5571, August 1975.
8. Robbiani, Raymond L., "Tactical Field Demonstration of Mobile Weather Radar Set AN/TPS-41 at Fort Rucker, Alabama," ECOM-5572, August 1975.
9. Miers, B., G. Blackman, D. Langer, and N. Lorimier, "Analysis of SMS/GOES Film Data," ECOM-5573, September 1975.
10. Manquero, Carlos, Louis Duncan, and Rufus Bruce, "An Indication from Satellite Measurements of Atmospheric CO2 Variability," ECOM-5574, September 1975.
11. Petracca, Carmine, and James D. Lindberg, "Installation and Operation of an Atmospheric Particulate Collector," ECOM-5575, September 1975.
12. Avara, Elton P., and George Alexander, "Empirical Investigation of Three Iterative Methods for Inverting the Radiative Transfer Equation," ECOM-5576, October 1975.
13. Alexander, George D., "A Digital Data Acquisition Interface for the SMS Direct Readout Ground Station — Concept and Preliminary Design," ECOM-5577, October 1975.
14. Cantor, Israel, "Enhancement of Point Source Thermal Radiation Under Clouds in a Nonattenuating Medium," ECOM-5578, October 1975.
15. Norton, Colburn, and Glenn Hoidale, "The Diurnal Variation of Mixing Height by Month over White Sands Missile Range, N.M," ECOM-5579, November 1975.
16. Avara, Elton P., "On the Spectrum Analysis of Binary Data," ECOM-5580, November 1975.
17. Taylor, Fredrick J., Thomas H. Pries, and Chao-Huan Huang, "Optimal Wind Velocity Estimation," ECOM-5581, December 1975.
18. Avara, Elton P., "Some Effects of Autocorrelated and Cross-Correlated Noise on the Analysis of Variance, " ECOM-5582, December 1975.
19. Gillespie, Patti S., R.L. Armstrong, and Kenneth O. White, "The Spectral Characteristics and Atmospheric CO2 Absorption of the Ho^{+3}:YLF Laser at $2.05\mu m$," ECOM-5583, December 1975.
20. Novlan, David J. "An Empirical Method of Forecasting Thunderstorms for the White Sands Missile Range," ECOM-5584, February 1976.
21. Avara, Elton P., "Randomization Effects in Hypothesis Testing with Autocorrelated Noise," ECOM-5585, February 1976.
22. Watkins, Wendell R., "Improvements in Long Path Absorption Cell Measurement," ECOM-5586, March 1976.
23. Thomas, Joe, George D. Alexander, and Marvin Dubbin, "SATTEL — An Army Dedicated Meteorological Telemetry System," ECOM-5587. March 1976.
24. Kennedy, Bruce W., and Delbert Bynum, "Army User Test Program for the RDT&E-XM-75 Meteorological Rocket," ECOM-5588, April 1976.

25. Barnett, Kenneth M., "A Description of the Artillery Meteorological Comparisons at White Sands Missle Range, October 1974 - December 1974 ('PASS' - Prototype Artillery [Meteorological] Subsystem)," ECOM-5589, April 1976.
26. Miller, Walter B., "Preliminary Analysis of Fall-of-Shot From Project 'PASS'," ECOM-5590, April 1976.
27. Avara, Elton P., "Error Analysis of Minimum Information and Smith's Direct Methods for Inverting the Radiative Transfer Equation," ECOM-5591, April 1976.
28. Yee, Young P., James D. Horn, and George Alexander, "Synoptic Thermal Wind Calculations from Radiosonde Observations Over the Southwestern United States," ECOM-5592, May 1976.
29. Duncan, Louis D., and Mary Ann Seagraves, "Applications of Empirical Corrections to NOAA-4 VTPR Observations," ECOM-5593, May 1976.
30. Miers, Bruce T., and Steve Weaver, "Applications of Meterological Satellite Data to Weather Sensitive Army Operations,"ECOM-5594, May 1976.
31. Sharenow, Moses, "Redesign and Improvement of Balloon ML-566," ECOM-5595, June, 1976.
32. Hansen, Frank V., "The Depth of the Surface Boundary Layer," ECOM-5596, June 1976.
33. Pinnick, R.G., and E.B. Stenmark, "Response Calculations for a Commercial Light-Scattering Aerosol Counter," ECOM-5597, July 1976.
34. Mason, J., and G.B. Hoidale, "Visibility as an Estimator of Infrared Transmittance," ECOM-5598, July 1976.
35. Bruce, Rufus E., Louis D. Duncan, and Joseph H. Pierluissi, "Experimental Study of the Relationship Between Radiosonde Temperatures and Radiometric-Area Temperatures," ECOM-5599, August 1976.
36. Duncan, Louis D., "Stratospheric Wind Shear Computed from Satellite Thermal Sounder Measurements," ECOM-5800, September 1976.
37. Taylor, F., P. Mohan, P. Joseph and T. Pries, "An All Digital Automated Wind Measurement System," ECOM-5801, September 1976.
38. Bruce, Charles, "Development of Spectrophones for CW and Pulsed Radiation Sources," ECOM-5802, September 1976.
39. Duncan, Louis D., and Mary Ann Seagraves,"Another Method for Estimating Clear Column Radiances," ECOM-5803, October 1976.
40. Blanco, Abel J., and Larry E. Taylor, "Artillery Meteorological Analysis of Project Pass," ECOM-5804, October 1976.
41. Miller, Walter, and Bernard Engebos," A Mathematical Structure for Refinement of Sound Ranging Estimates," ECOM-5805, November, 1976.
42. Gillespie, James B., and James D. Lindberg, "A Method to Obtain Diffuse Reflectance Measurements from 1.0 to 3.0 μm Using a Cary 17I Spectrophotometer," ECOM-5806, November 1976.
43. Rubio, Roberto, and Robert O. Olsen,"A Study of the Effects of Temperature Variations on Radio Wave Absorption,"ECOM-5807, November 1976.
44. Ballard, Harold N., "Temperature Measurements in the Stratosphere from Balloon-Borne Instrument Platforms, 1968-1975," ECOM-5808, December 1976.
45. Monahan, H.H., "An Approach to the Short-Range Prediction of Early Morning Radiation Fog," ECOM-5809, January 1977.
46. Engebos, Bernard Francis, "Introduction to Multiple State Multiple Action Decision Theory and Its Relation to Mixing Structures," ECOM-5810, January 1977.
47. Low, Richard D.H.,"Effects of Cloud Particles on Remote Sensing from Space in the 10-Micrometer Infrared Region," ECOM-5811, January 1977.
48. Bonner, Robert S., and R. Newton, "Application of the AN/GVS-5 Laser Rangefinder to Cloud Base Height Measurements," ECOM-5812, February 1977.
49. Rubio, Roberto, "Lidar Detection of Subvisible Reentry Vehicle Erosive Atmospheric Material," ECOM-5813, March 1977.
50. Low, Richard D.H., and J.D. Horn, "Mesoscale Determination of Cloud-Top Height: Problems and Solutions," ECOM-5814, March 1977.

51. Duncan, Louis D., and Mary Ann Seagraves, "Evaluation of the NOAA-4 VTPR Thermal Winds for Nuclear Fallout Predictions," ECOM-5815, March 1977.
52. Randhawa, Jagir S., M. Izquierdo, Carlos McDonald and Zvi Salpeter, "Stratospheric Ozone Density as Measured by a Chemiluminescent Sensor During the Stratcom VI-A Flight," ECOM-5816, April 1977.
53. Rubio, Roberto, and Mike Izquierdo, "Measurements of Net Atmospheric Irradiance in the 0.7- to 2.8-Micrometer Infrared Region," ECOM-5817, May 1977.
54. Ballard, Harold N., Jose M. Serna, and Frank P. Hudson Consultant for Chemical Kinetics, "Calculation of Selected Atmospheric Composition Parameters for the Mid-Latitude, September Stratosphere," ECOM-5818, May 1977.
55. Mitchell, J.D., R.S. Sagar, and R.O. Olsen, "Positive Ions in the Middle Atmosphere During Sunrise Conditions," ECOM-5819, May 1977.
56. White, Kenneth O., Wendell R. Watkins, Stuart A. Schleusener, and Ronald L. Johnson, "Solid-State Laser Wavelength Identification Using a Reference Absorber," ECOM-5820, June 1977.
57. Watkins, Wendell R., and Richard G. Dixon, "Automation of Long-Path Absorption Cell Measurements," ECOM-5821, June 1977.
58. Taylor, S.E., J.M. Davis, and J.B. Mason, "Analysis of Observed Soil Skin Moisture Effects on Reflectance," ECOM-5822, June 1977.
59. Duncan, Louis D. and Mary Ann Seagraves, "Fallout Predictions Computed from Satellite Derived Winds," ECOM-5823, June 1977.
60. Snider, D.E., D.G. Murcray, F.H. Murcray, and W.J. Williams, "Investigation of High-Altitude Enhanced Infrared Backround Emissions" (U), SECRET, ECOM-5824, June 1977.
61. Dubbin, Marvin H. and Dennis Hall, "Synchronous Meteorlogical Satellite Direct Readout Ground System Digital Video Electronics," ECOM-5825, June 1977.
62. Miller, W., and B. Engebos, "A Preliminary Analysis of Two Sound Ranging Algorithms," ECOM-5826, July 1977.
63. Kennedy, Bruce W., and James K. Luers, "Ballistic Sphere Techniques for Measuring Atomspheric Parameters," ECOM-5827, July 1977.
64. Duncan, Louis D., "Zenith Angle Variation of Satellite Thermal Sounder Measurements," ECOM-5828, August 1977.
65. Hansen, Frank V., "The Critical Richardson Number," ECOM-5829, September 1977.
66. Ballard, Harold N., and Frank P. Hudson (Compilers), "Stratospheric Composition Balloon-Borne Experiment," ECOM-5830, October 1977.
67. Barr, William C., and Arnold C. Peterson, "Wind Measuring Accuracy Test of Meteorological Systems," ECOM-5831, November 1977.
68. Ethridge, G.A. and F.V. Hansen, "Atmospheric Diffusion: Similarity Theory and Empirical Derivations for Use in Boundary Layer Diffusion Problems," ECOM-5832, November 1977.
69. Low, Richard D.H., "The Internal Cloud Radiation Field and a Technique for Determining Cloud Blackness," ECOM-5833, December 1977.
70. Watkins, Wendell R., Kenneth O. White, Charles W. Bruce, Donald L. Walters, and James D. Lindberg, "Measurements Required for Prediction of High Energy Laser Transmission," ECOM-5834, December 1977.
71. Rubio, Robert, "Investigation of Abrupt Decreases in Atmospherically Backscattered Laser Energy," ECOM-5835, December 1977.
72. Monahan, H.H. and R.M. Cionco, "An Interpretative Review of Existing Capabilities for Measuring and Forecasting Selected Weather Variables (Emphasizing Remote Means)," ASL-TR-0001, January 1978.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1977 777-093/28

48